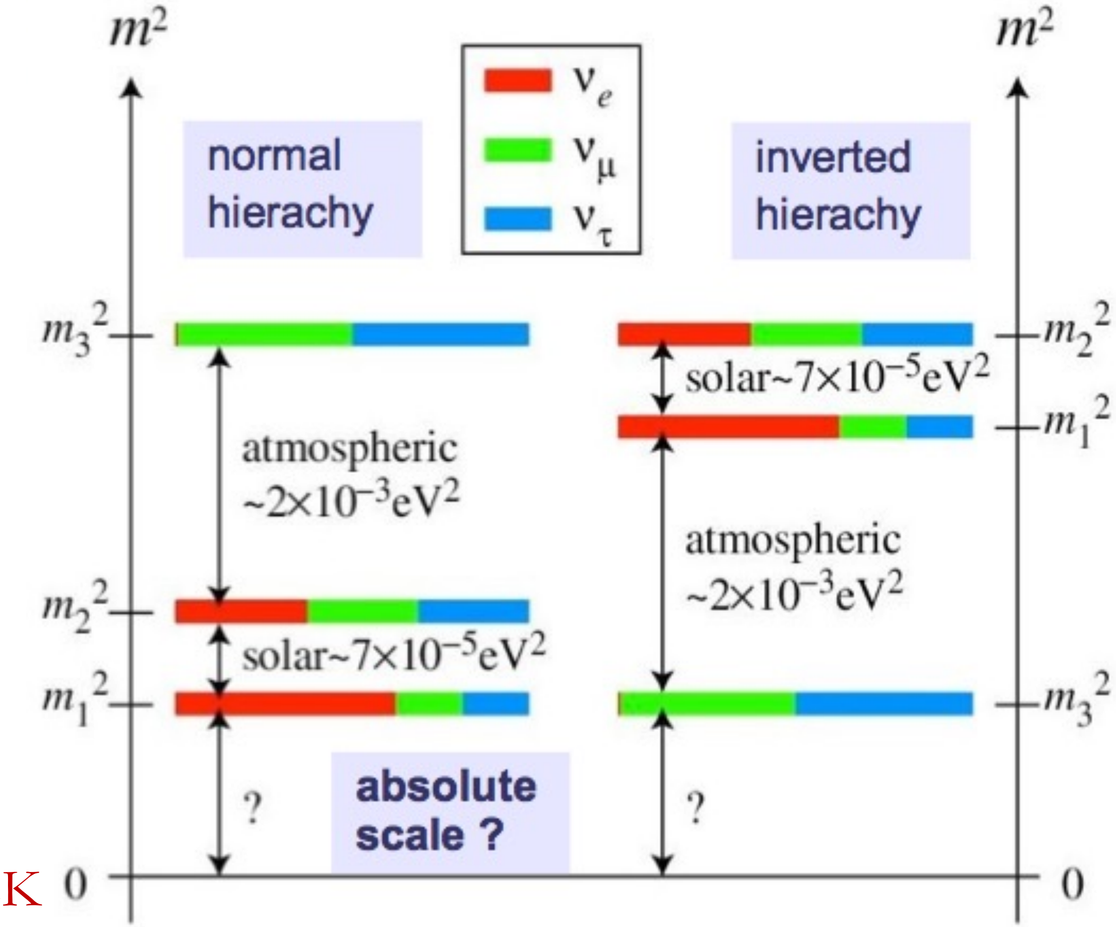
What we know (from ν osc.):

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm^2 values known (with varying accuracies)

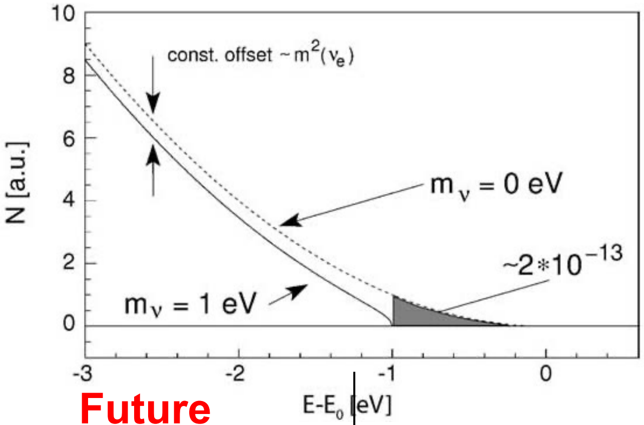
What we don't know:

- Normal or inverted hierarchy?
- Absolute mass scale? (only upper limits)
- Dirac or Majorana particle?
- CP violating phase in mixing matrix? Now first hints from T2K
- Existence of sterile neutrinos?



How “to weight” neutrinos?

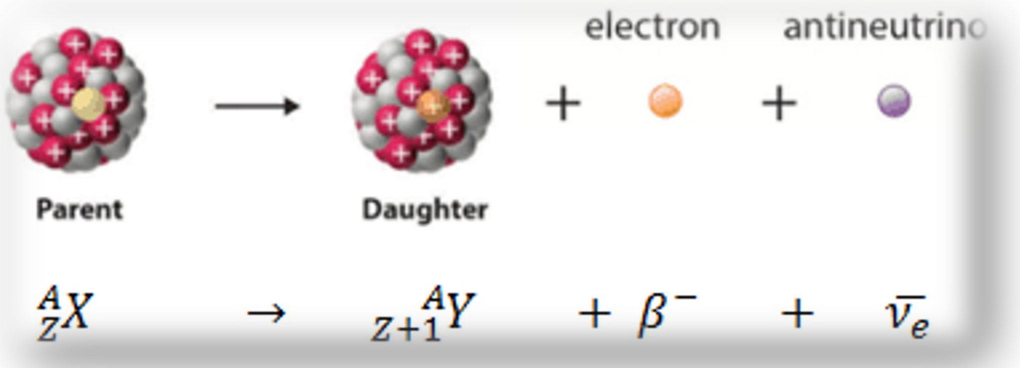
- Neutrino Oscillations
- Cosmology
- Direct Beta Decay Endpoint
- Double Beta Decay



Tools	**Present sensitivity**	**Future sensitivity (a few year scale)**
Cosmology (CMB + LSS)	120 meV	50 meV
Neutrinoless Double Beta Decay	100 meV	20-50 meV
Single Beta Decay	1.1 eV	0.2 eV

β decay

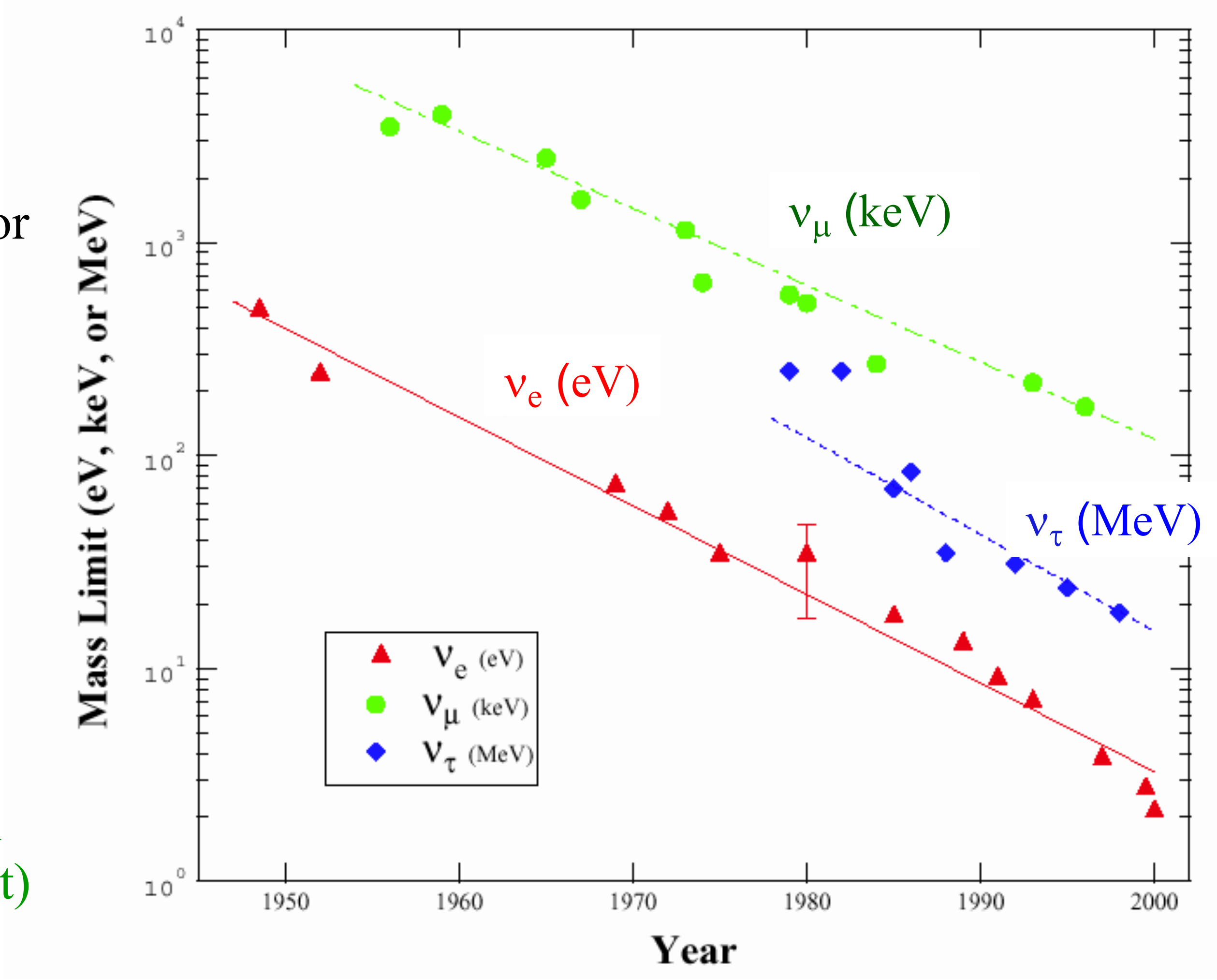
- Event: $(A, Z) \rightarrow (A, Z+1) + e^{-} + \bar{\nu}_e$
- Observable: $m_\beta = \sqrt{\sum_k |U_{ek}|^2 m_k^2}$
- Model-dependent: NO
- Dirac or Majorana: both
- Present stage: <2.2 eV (MAINZ - TROITSK)
  <1.1 eV (KATRIN)
- Sensitivity expts next generation: 0.2 eV



Direct Neutrino Mass Experiments

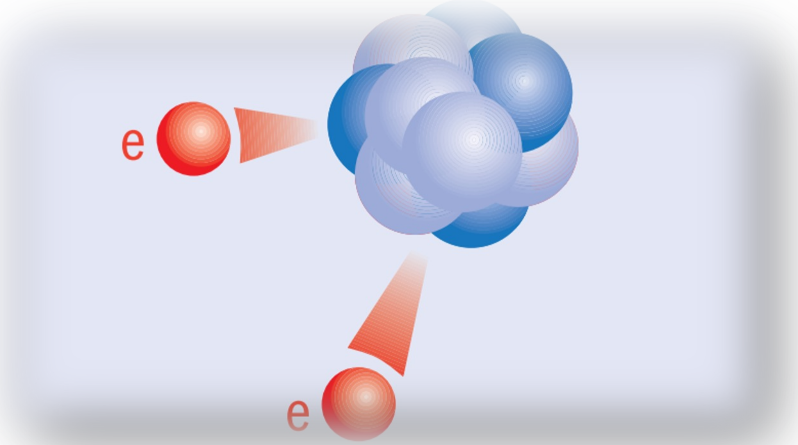
- Techniques
  - Electron neutrino:
    - Study E_e end point for $^3H \rightarrow ^3He + \nu_e + e^-$
  - Muon neutrino:
    - Measure P_μ in $\pi \rightarrow \mu\nu_\mu$ decays
  - Tau neutrino:
    - Study $n\pi$ mass in $\tau \rightarrow (n\pi)\ \nu_\tau$ decays

(Also, information from Supernova time-of-flight)



$0\nu\beta\beta$ decay

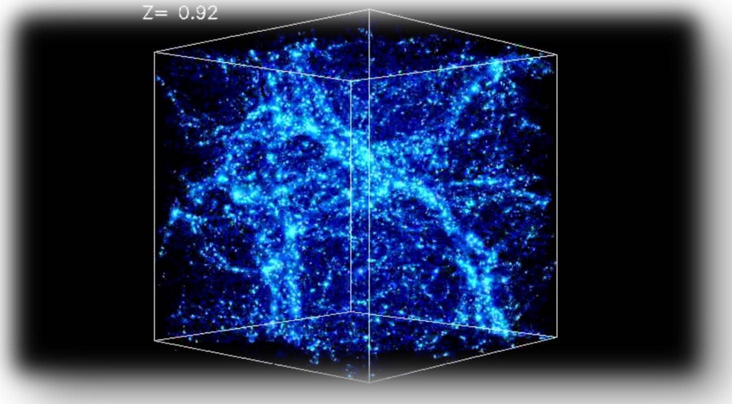
Event:	$(A,Z) \rightarrow (A,Z+2) + 2e^-$
Observable:	$m_{\beta\beta} = \left\lvert \sum_k U_{ek}^2 m_k \right\rvert$ (*)
Model-dependent:	YES
Dirac or Majorana:	Majorana
Present stage:	<100 meV
Sensitivity expts next generation:	20-50 meV

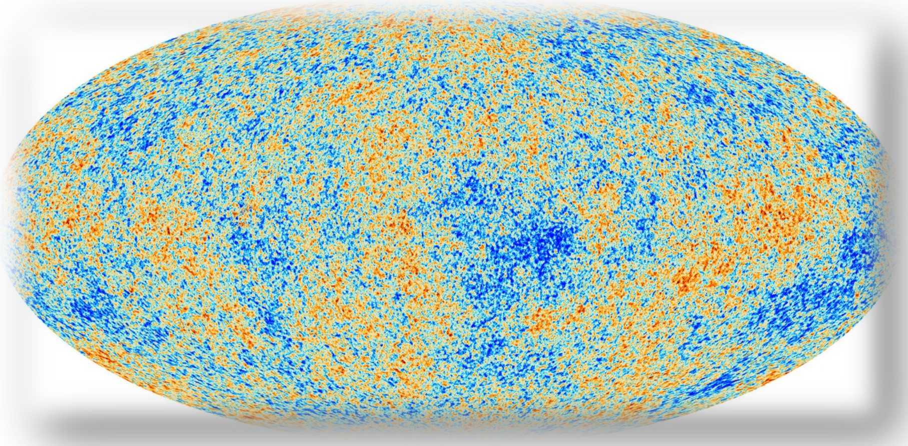


(*) Possible cancellations due to the presence of Majorana phases

Cosmology

- Event: CMB anisotropies, LSS
- Observable: $m_{cosmo} = \sum_k m_k$
- Model-dependent: YES, strongly
- Dirac or Majorana: both
- Present stage: <120 meV (CMB+LSS)
- Sensitivity expts next generation: 50 meV





Complementarity of cosmology, single and double β decay

Cosmology, **single** and **double β** decay measure different combinations of the neutrino mass eigenvalues, constraining the neutrino mass scale

In a standard three active neutrino scenario:

$$m_{cosmo} = \sum_{k=1}^{3} m_k$$

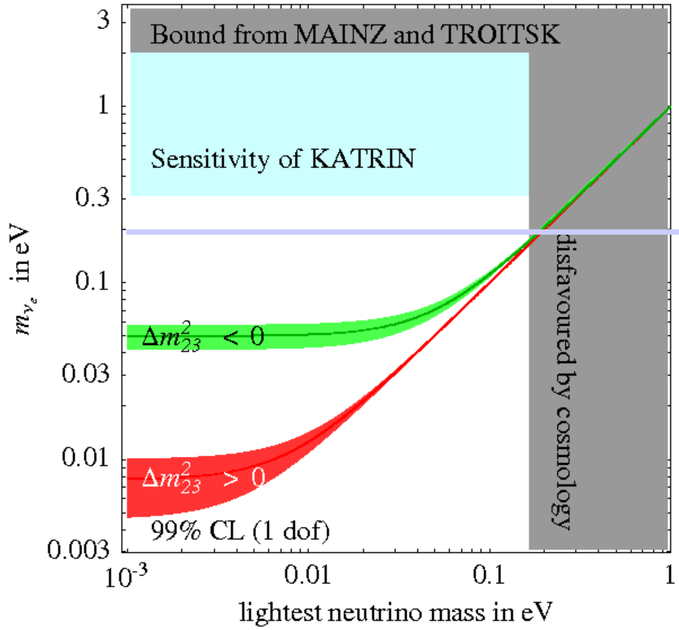
cosmology
simple sum
pure kinematical effect

$$m_\beta = \sqrt{\sum_{k=1}^{3} |U_{ek}|^2 m_k^2}$$

beta decay
incoherent sum of
real neutrino

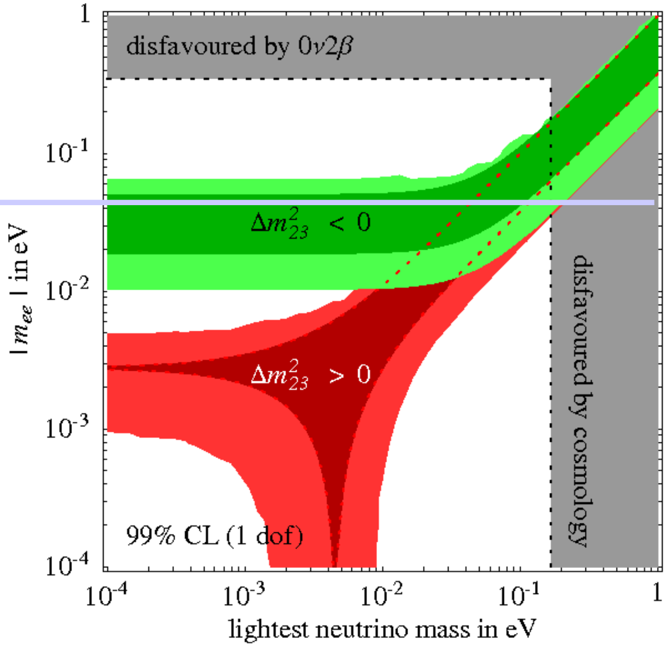
$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| = \left|\sum_{k=1}^{3} |U_{ek}|^2 e^{i\alpha_k}\, m_k\right|$$

double beta decay
coherent sum
virtual neutrino
Majorana phases



m_{ν_e}

0.2 eV



m_{ee}

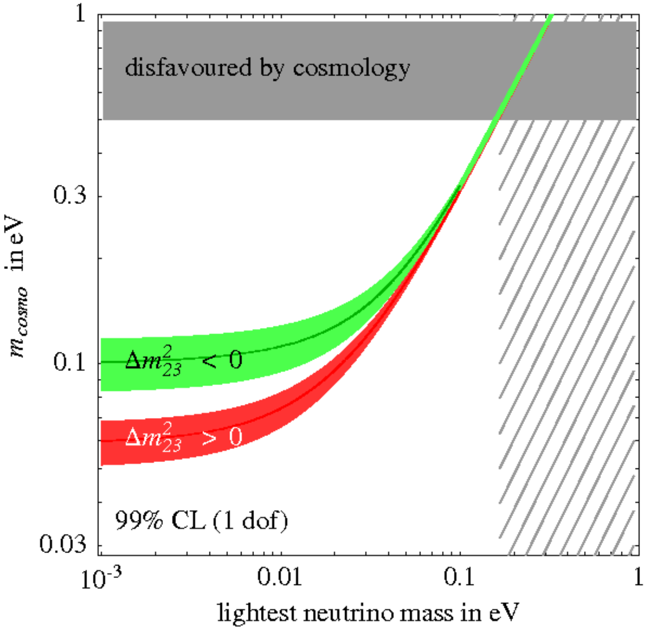
0.05 eV

$\Delta m^2_{23} < 0$

Inverted hierarchy

$\Delta m^2_{23} > 0$

Normal hierarchy



m_{cosmo}

A.Strumia, F.Vissani, *Neutrino masses and mixings and...* , hep-ph/0606054v2

Neutrino mass determination from:

- cosmology
- β decay
- $0\nu\beta\beta$ decay

Early Universe – Neutrino Decoupling

In the early Universe the particles were in thermal equilibrium

$d^3p = 4\pi p^2 dp = 4\pi pEdE$

The equilibrium number density of Fermi (Bose) particles of the type *i*

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{\sqrt{E^2-m_i^2}\;E\,dE}{e^{\frac{E-\mu_i}{kT_i}} \pm 1}$$

The equilibrium energy density

$$\rho_i = \frac{g}{2\pi^2}\int_0^\infty \frac{\sqrt{E^2-m_i^2}\;E^2\,dE}{e^{\frac{E-\mu_i}{kT_i}} \pm 1}$$

In the ultra-relativistic case $kT_i \gg m_i\,,\ \mu_i$

$\zeta(3) = 1.202$ ($\zeta(n)$ is the Riemann zeta function)

$$n_i = \frac{\zeta(3)}{\pi^2} g_i\,(kT_i)^3\ \text{(Bose)}, \qquad n_i = \left(\frac{3}{4}\right)\frac{\zeta(3)}{\pi^2} g_i\,(kT_i)^3\ \text{(Fermi)}$$

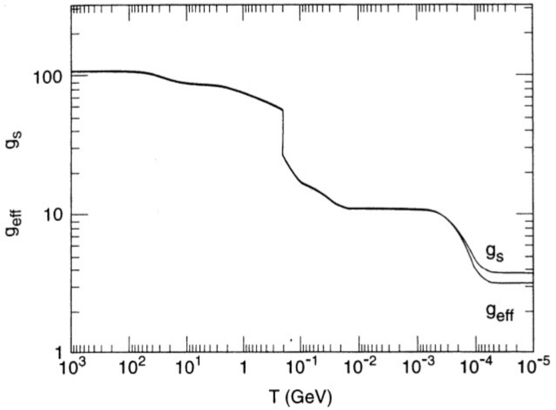
$$\rho_i = \frac{\pi^2}{30} g_i\,(kT_i)^4\ \text{(Bose)}, \qquad \rho_i = \left(\frac{7}{8}\right)\frac{\pi^2}{30} g_i\,(kT_i)^4\ \text{(Fermi)}$$

$$g_* = \sum_{\text{bosons}} g_i \left(\frac{T_i}{T}\right)^4 + \left(\frac{7}{8}\right)\sum_{\text{fermions}} g_i \left(\frac{T_i}{T}\right)^4$$

Effective number of degrees of freedom of ultra-relativistic particles

The total energy density

$$\rho = \sum_i \rho_i = \frac{\pi^2}{30} g_*(kT)^4$$



Neutrino decouples from plasma at $T \approx 1$ MeV. When the temperature drops, $e^\pm$ begin to annihilate. The released energy heats up only γ's because neutrinos are decoupled. Thus, after the decoupling of photons their temperature will be higher than the neutrino temperature.

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T.$$

$$n_\gamma = \frac{\zeta(3)}{\pi^2} g_\gamma (kT)^3, \quad g_\gamma = 2.$$

$$n_\nu = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_\nu (kT_\nu)^3, \quad g_\nu = 6.$$

$$\Longrightarrow n_\nu = \frac{9}{11} n_\gamma$$

$$n_\gamma = 410.5\ \text{cm}^{-3}$$

$$n_\nu = 336\ \text{cm}^{-3}$$

$n_B = 2.5 \cdot 10^{-7}\ \text{cm}^{-3}$

photons and neutrinos are the most abundant particles in the Universe

Cosmological (Massless) Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68\cdot 10^{-4} eV \qquad T_\gamma = 2.725\ \mathrm{K}$$

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827\cdot T_\nu^3 \approx 112cm^{-3}$$

for a relativistic neutrino translates in a extra radiation component of:

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8}\frac{g_\nu}{g_\gamma}\left(\frac{T_\nu}{T_\gamma}\right)^4$$

$$\Omega_\nu h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^\nu \Omega_\gamma h^2$$

Standard Model predicts:

$$N_{eff}^\nu = 3.046$$

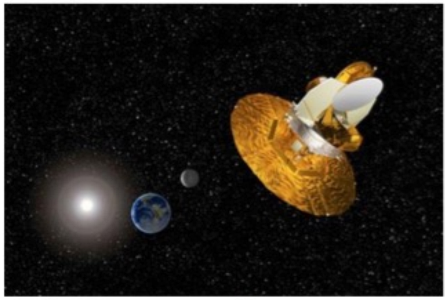
$$\boxed{\Omega_\nu = \frac{\rho_\nu^0}{\rho_{\mathrm{crit}}^0} = \frac{\sum m_\nu}{93.14h^2\ \mathrm{eV}}}$$

Measurements on Ω_ν give info on $m_{cosmo} = \sum m_\nu$

Precision cosmology

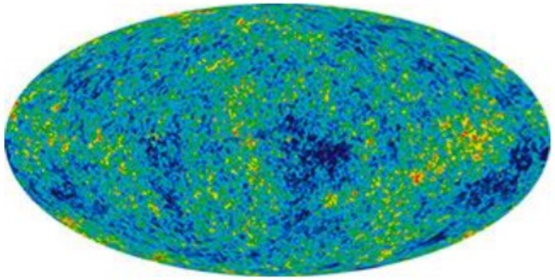
approaches to estimate the absolute neutrino mass scale

Cosmology: fluctuations of the early universe density from cosmic microwave background

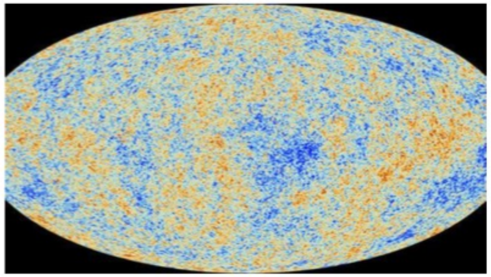


WMAP spacecraft

PLANCK spacecraft



WMAP's maps the afterglow of the hot, young universe when it was only 375,000 years old



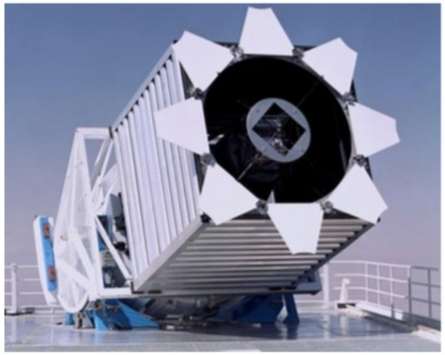
Planck's map of the young universe

- The visible structure of the universe has been formed out by fluctuations at the very early stage. Due to the large abundance of relic neutrinos and their low masses they acted as hot dark matter: neutrinos have smeared out fluctuations at small scales.

- Measurements of differences in the temperature of the cosmic microwave background (CMB) – the radiant heat remaining from the Big Bang – across the sky
- The early fluctuations of universe density imprinted on the cosmic microwave background measured with the WMAP satellite
- The Planck apparatus shows agreement with the WMAP results on the density and distribution of matter in the Universe.

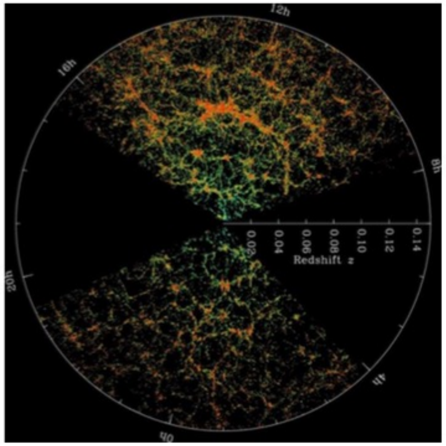
Precision cosmology

Cosmology: mapping out today's structure of the universe by large galaxy surveys



The Sloan Foundation 2.5m Telescope at Apache Point Observatory

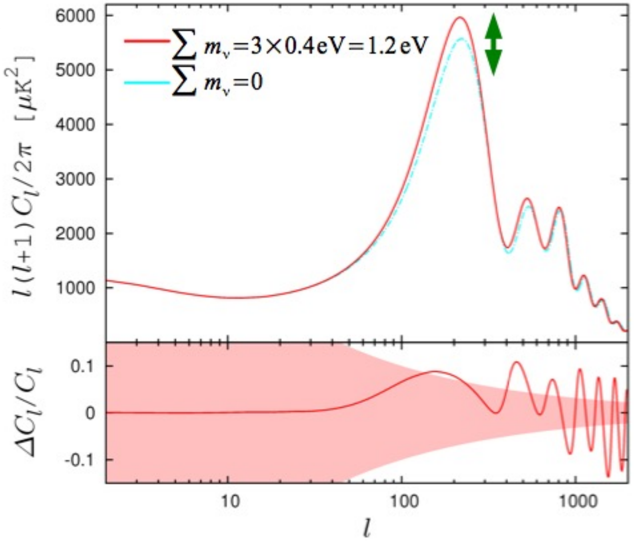
The SDSS map of the Universe. Each dot is a galaxy; the color bar shows the local density →



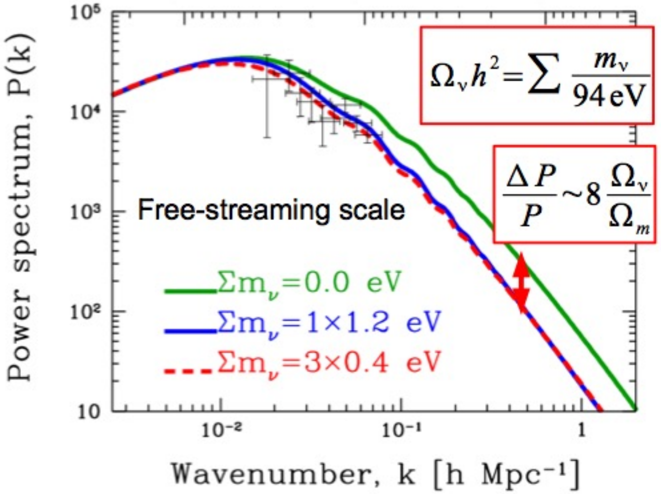
- Approaches to estimate the absolute neutrino mass scale
- SDSS is a multi-filter imaging and spectroscopic redshift survey using a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico, United States.

- SDSS map of the large-scale structure of the universe
- The Sloan Digital Sky Survey has been working for more than 15 years to make the most detailed three-dimensional maps of the Universe, with deep multi-color images of one third of the sky, and spectra for more than three million astronomical objects.

- **CMB** probes the relativistic to non-relativistic transition of neutrinos via the early ISW effect.

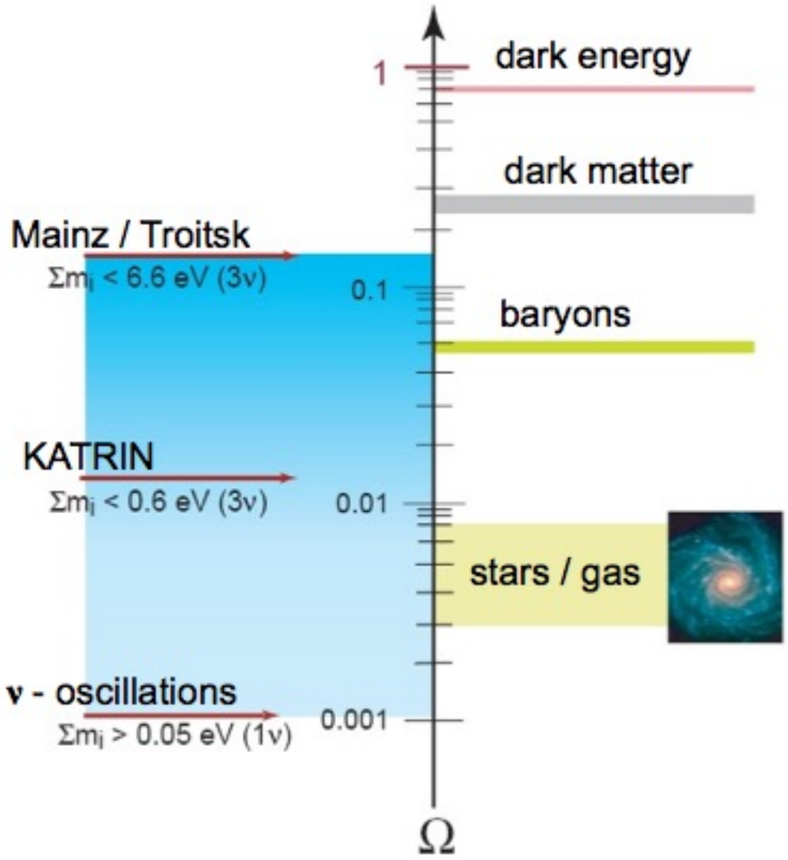


- **LSS** measures suppression of power on small scales due to non-clustering neutrinos.

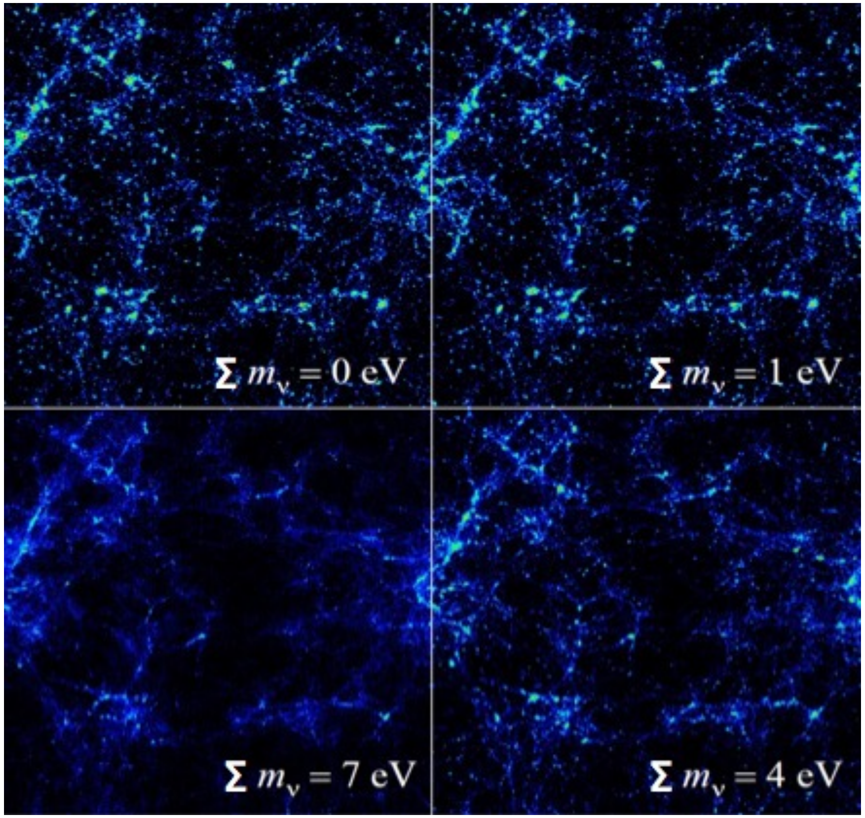


Large Scale Structures (LSS)

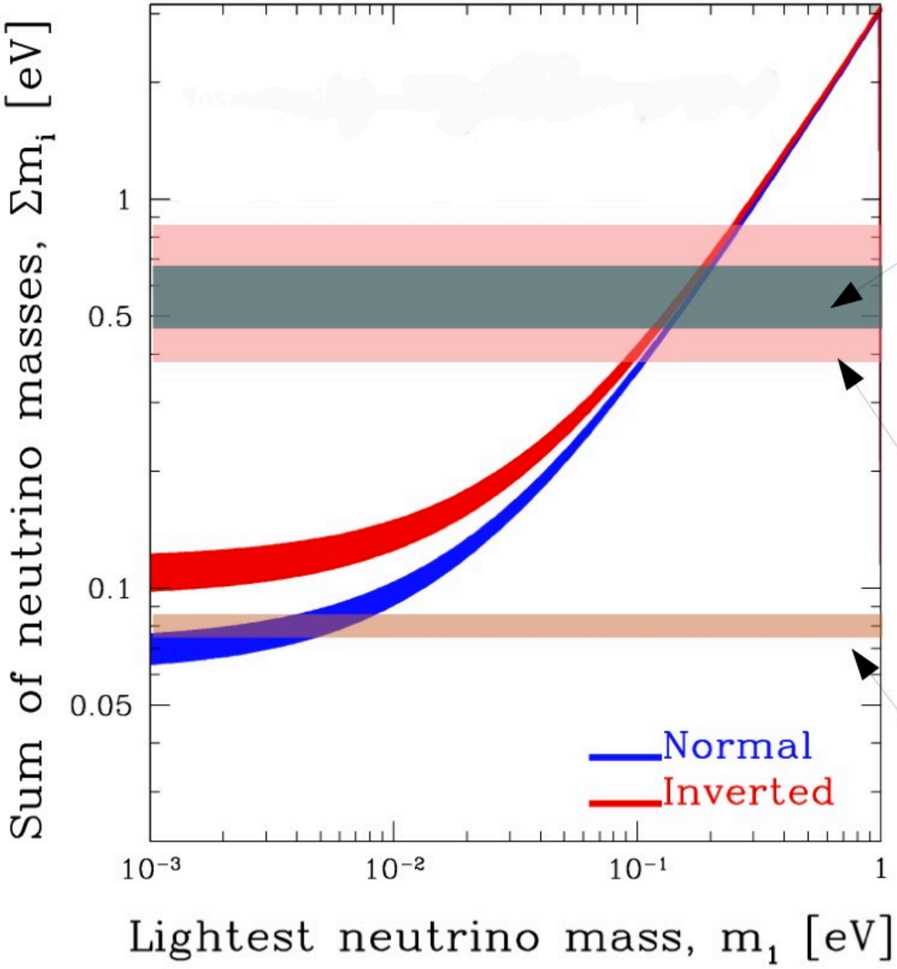
- Neutrinos are (after γ's) the second most abundant particle species in the universe
- As part of the hot dark matter, neutrinos have a significant influence on structure formation



For large Σm_ν values fine grained structures are washed out by the free streaming neutrinos



Present constraints and future sensitivities...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

$$\sum m_\nu < 0.44 \rightarrow 0.76\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y^3W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

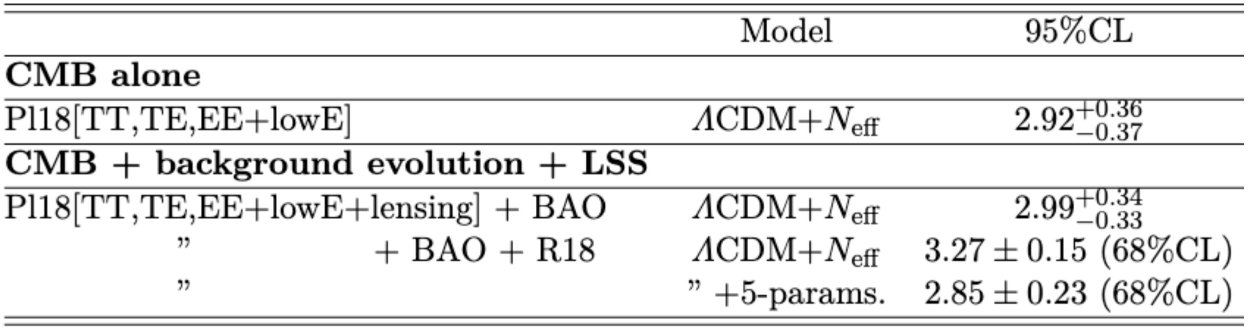
Perotto et al. 2006

Planck+Weak lensing (LSST)

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

Hannestad, Tu & Y^3W 2006

Summary of $N_{\rm eff}$ constraints.

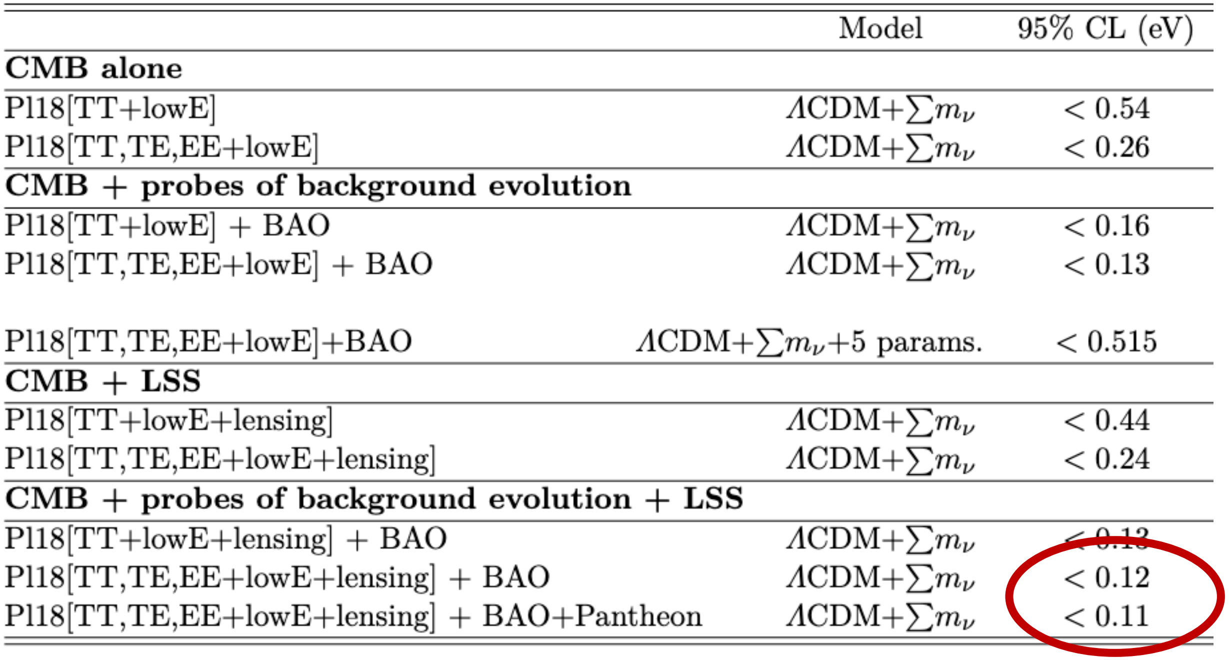


	Model	95%CL
CMB alone		
Pl18[TT,TE,EE+lowE]	ΛCDM+$N_{\rm eff}$	$2.92^{+0.36}_{-0.37}$
CMB + background evolution + LSS		
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$2.99^{+0.34}_{-0.33}$
” + BAO + R18	ΛCDM+$N_{\rm eff}$	3.27 ± 0.15 (68%CL)
”	” +5-params.	2.85 ± 0.23 (68%CL)

$N_{\rm eff}$ = 3.045 is the Standard Model reference value

- Pl18 = Planck 2018 data
- high-l temperature + polarization likelihood (TT,TE,EE)
- low-l polarization (low E)
- CMB lensing spectrum likelihood (lensing) based on lensing extraction from quadratic estimators
- BAO refers to measurements of the BAO scale (and hence of the angular diameter distance)
- R18 refers to the distance ladder local measurement of the Hubble scale from cepheids and supernovae
- Pantheon refers to the supernovae Type Ia compilation

Summary of $\sum m_\nu$ constraints.



	Model	95% CL (eV)
CMB alone		
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26
CMB + probes of background evolution		
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.16
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515
CMB + LSS		
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24
CMB + probes of background evolution + LSS		
Pl18[TT+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.12
Pl18[TT,TE,EE+lowE+lensing] + BAO+Pantheon	ΛCDM+$\sum m_\nu$	< 0.11

Conclusions:

- $N_{\rm eff}$=0 is excluded at high CL. We need a neutrino background to explain CMB observation
- No evidence for extra radiation from CMB only measurements
- $N_{\rm eff}$=4 begins to be inconsistent

Neutrino mass determination from β decay

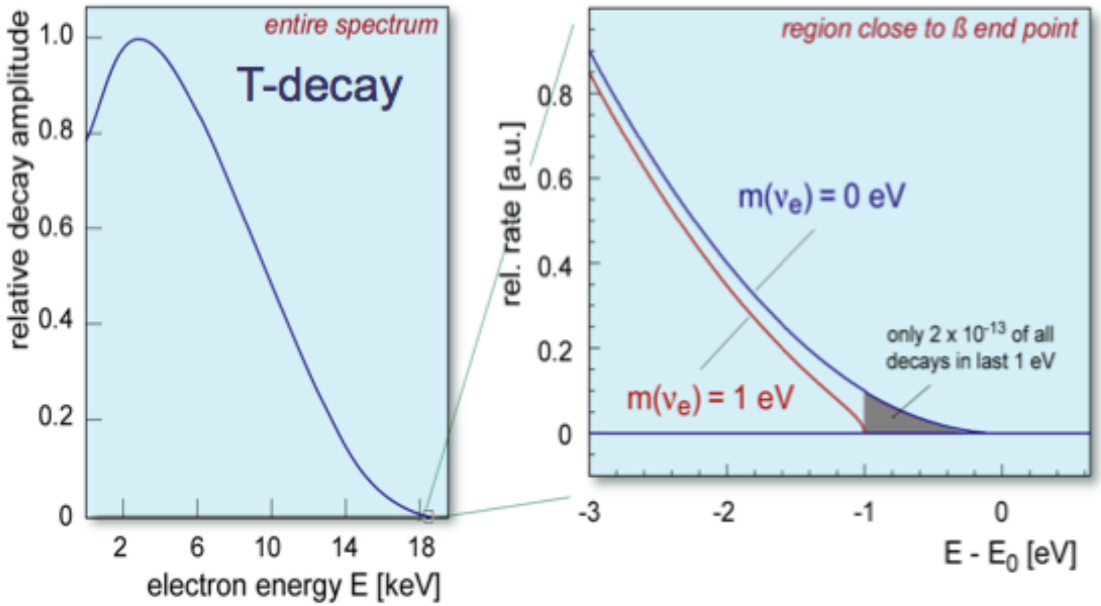
$$^{Z}_{A}X \rightarrow {}^{Z+1}_{A}Y + e^{-} + \bar{\nu}_e$$

$$\frac{d\Gamma}{dE} = C\,p(E+m_e)(E_0-E)\sqrt{(E_o-E)^2-m_{\nu_e}^2}\,F(Z+1,E)\,\Theta(E_0-E-m_{\nu_e})\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C\,|M|^2$$

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3}|U_{ei}|^2 m_i^2}$$

(modified by final states, recoil corrections, radiative corrections, ...)



Suitable β emitters:

Tritium

- E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a
- S(E) = 1 (super-allowed)

Rhenium

- E_0 = 2.47 keV, $T_{1/2}$ = 43.2 Gy

alternative approach:

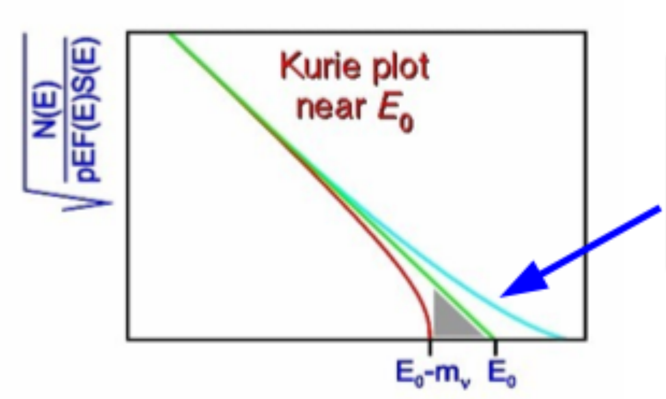
Holmium (EC decay)

- Q_{EC} ≈ 2.5 keV, $T_{1/2}$ = 4570 y

Main experimental approaches

Detector requirements:

- large solid angle
- high energy resolution
- low background
- low dead time / no pile up



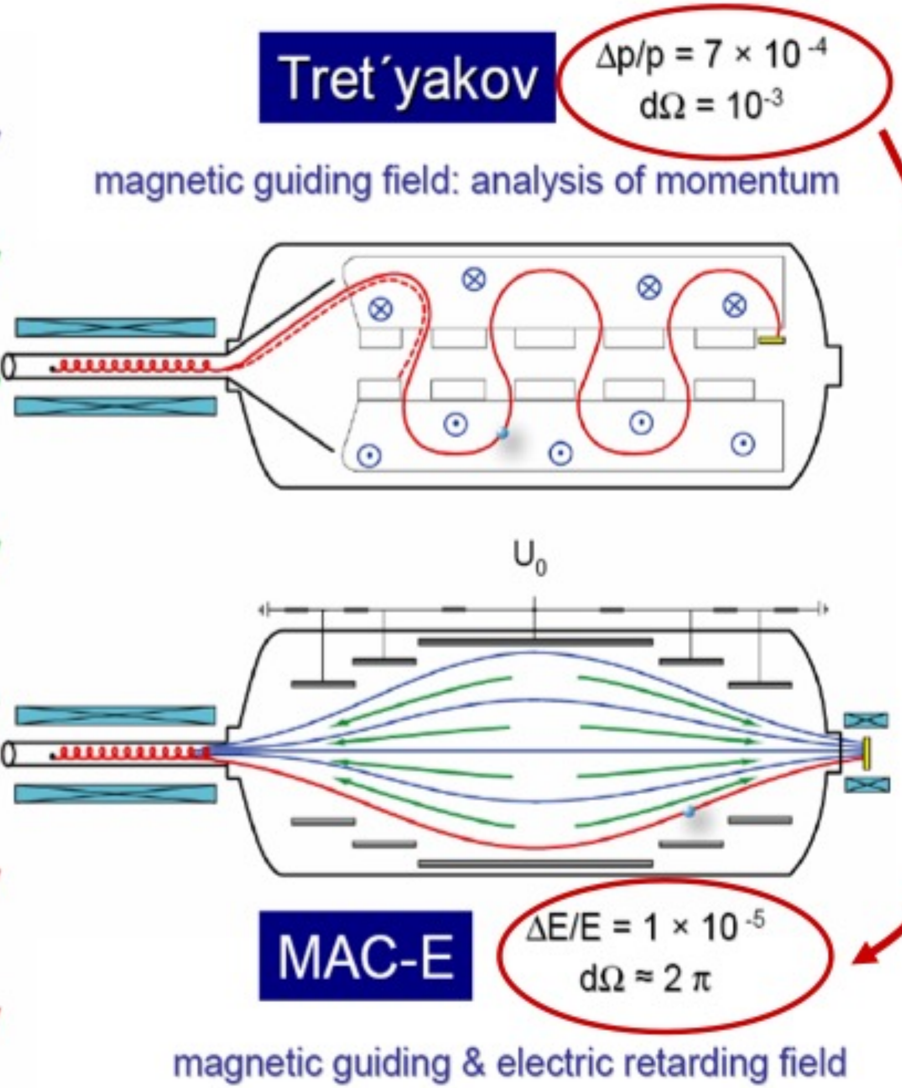
effect of :

- background
- pile up
- fluctuations

	calorimeter approach (MARE)	**spectrometer approach (KATRIN)**
source	metallic Re / dielectric $AgReO_4$	high purity T_2
activity	low : < 10^5 β/s, ≈ 1Bq/mg Re	high: ≈ 10^5 β/s, 4.7 Ci/s injection
technique	single crystal bolometers	electrostatic spectrometer
solid angle	4π (source = detector)	40% of 2π (max. forw. angle 51°)
response	entire β-decay energy	kinetic energy of β-decay electrons
interval	entire spectrum	narrow interval close to E_0
method	differential energy spectrum	integrated energy spectrum
setup	modular size, scalable	integral design, size limits
resolution	ΔE ~ 11-25 eV (FWHM)	ΔE ~ 0.93 eV (100%)

Historical hints of Tritium measurements

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.05 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV



Tret´yakov

$\Delta p/p = 7 \times 10^{-4}$
$d\Omega = 10^{-3}$

magnetic guiding field: analysis of momentum

MAC-E

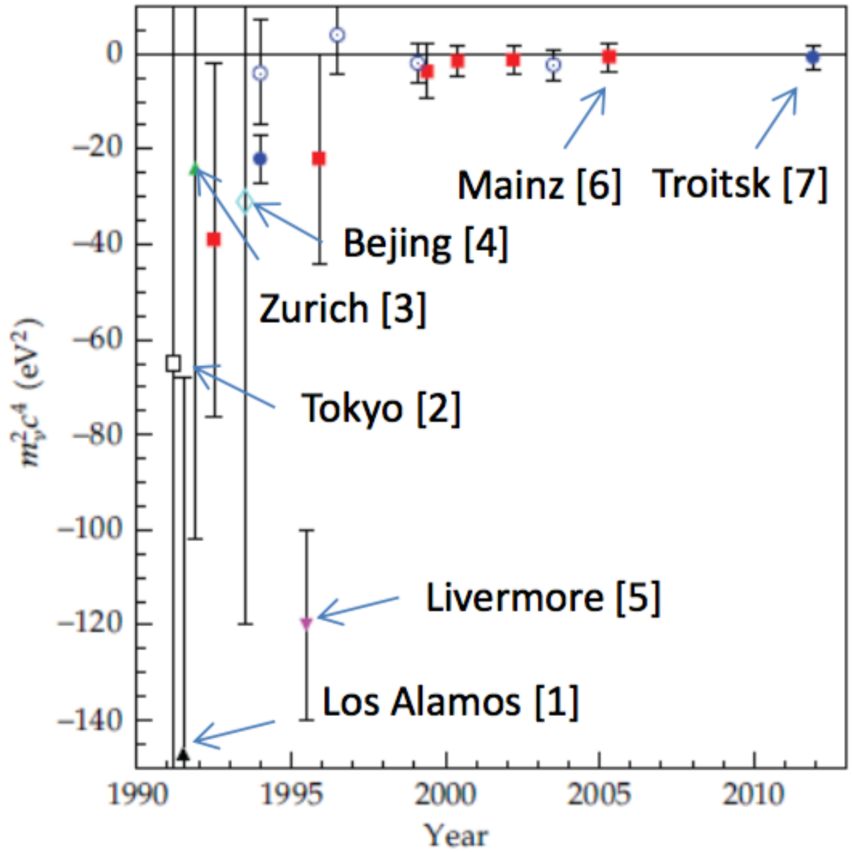
$\Delta E/E = 1 \times 10^{-5}$
$d\Omega \approx 2\pi$

magnetic guiding & electric retarding field

Neutrino mass

Direct neutrino mass determination

- Neutrino mass from tritium β-decay: early experiments



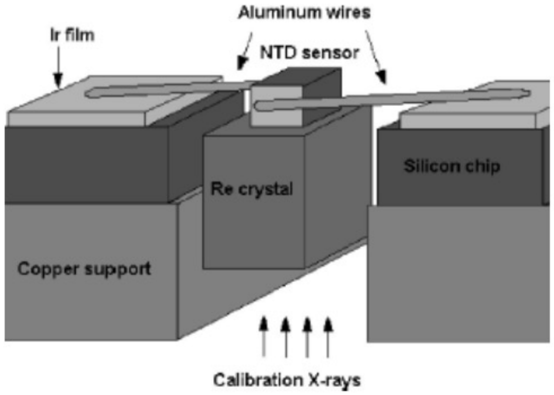
- Results of tritium β-decay experiments on the ***observable $m^2(\nu_e)$***.The experiments at Los Alamos, Zurich, Tokyo, Beijing, and Livermore used magnetic spectrometers; the tritium experiments at Mainz and Troitsk applied electrostatic spectrometers of the MAC-E-Filter type.
- The negative values of $m^2(\nu_e)$ have **no physical meaning**. The main reasons:
  - ✓ Some experiments (also Mainz) used as tritium source a film of molecular tritium quench condensed onto aluminum or graphite substrates. Although the film was prepared as a homogenous thin film with flat surface, detailed studies showed that the film was not stable: it underwent a temperature-activated roughening transition into an inhomogeneous film **by forming microcrystals**. Thus, unexpected large inelastic scattering probabilities were obtained, which were not taken into account in previous analyses. This extra energy losses were only significant when analyzing larger energy intervals below the endpoint.
  - ✓ The **missing experimental broadening** with Gaussian width σ. One expects a shift of the result on $m^2(\nu_e)$ of $\Delta m^2(\nu_e) \approx -2\sigma^2$, which gives rise to a negative value of $m^2(\nu_e)$

[1] R.G.H. Robertson et al., Limit on anti-ν_e mass from the observation of the β decay of molecular tritium, *PRL.* 67 (1991) 957
[2] H. Kawakami et al., “New upper bound on the electron anti-neutrino mass,” *PLB* 256 (1991) 105
[3] E. Holzschuh et al., Measurement of the electron neutrino mass from tritium β-decay, *PLB* 287 (1992) 381
[4] C. R.Ching et al., Apossible explanation of the negative values of $m^2 v_e$ obtained from the β spectrum shape analyses, *Int. J Mod. Phys. A* 10 (1995) 2841
[5] W. Stoeffl and D.J. Decman, Anomalous structure in the β decay of gaseous molecular tritium, *PRL* 75 (1995) 3237
[6] C. Kraus et al., Final results from phase II of the Mainz neutrino mass search in tritium β decay, Eur. Phys. J C 40 (2005) 447.
[7] V. N. Aseev et al., Upper limit on the electron antineutrino mass from the Troitsk experiment, Phys. Rev. D 84 (2011) 112003

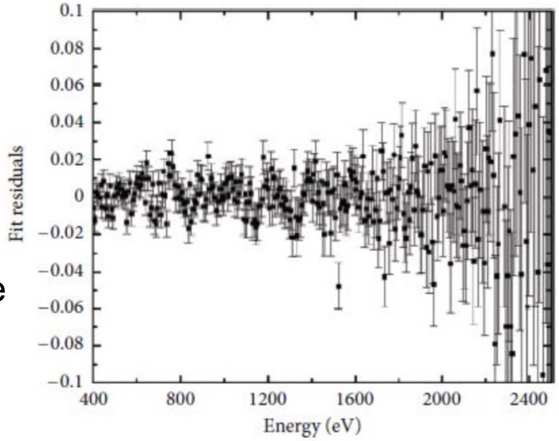
Neutrino mass

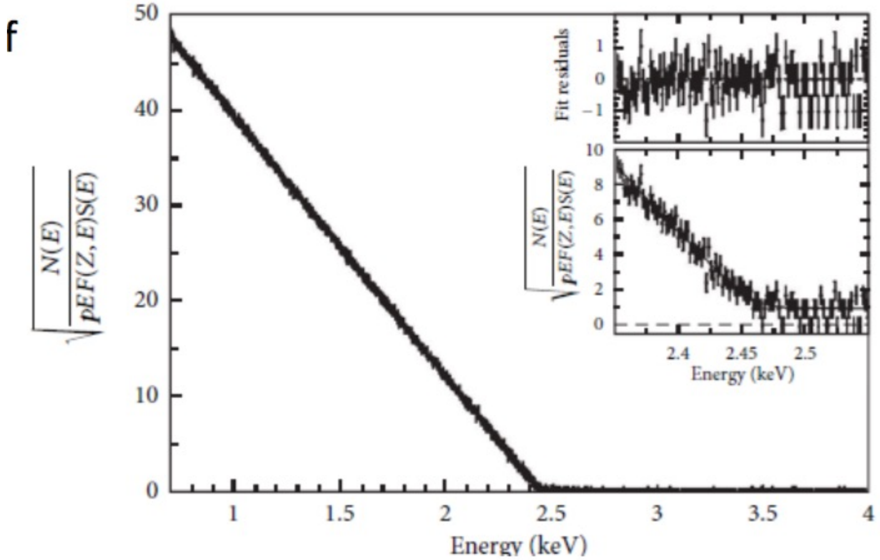
Direct neutrino mass determination

- Cryobolometers: measurements of ^{187}Re β-spectrum



- **MANU** expt. used a single metallic rhenium crystal of about 1.6 mg as absorber read out by a neutron transmutation doped (NTD) germanium thermistor
- The residuals of the theoretically expected ^{187}Re β-spectrum that has been fitted to the data exhibit effects of a β-environmental fine structure (BEFS) modulation most clearly visible at low electron energies





- Kurie plot of the experimental ^{187}Re β- spectrum obtained by the MiBeta collaboration

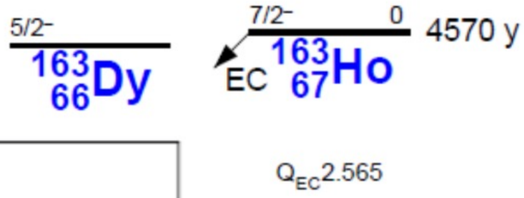
- **MiBeta**. The experiment has been carried out with an array of eight $AgReO_4$ thermal detectors operating at T=100 mK
- An average energy resolution FWHM= 28.5 eV was achieved. The analysis of the spectrum near the endpoint resulted in an upper limit $m(\nu_e) < 15$ eV at 90% CL.

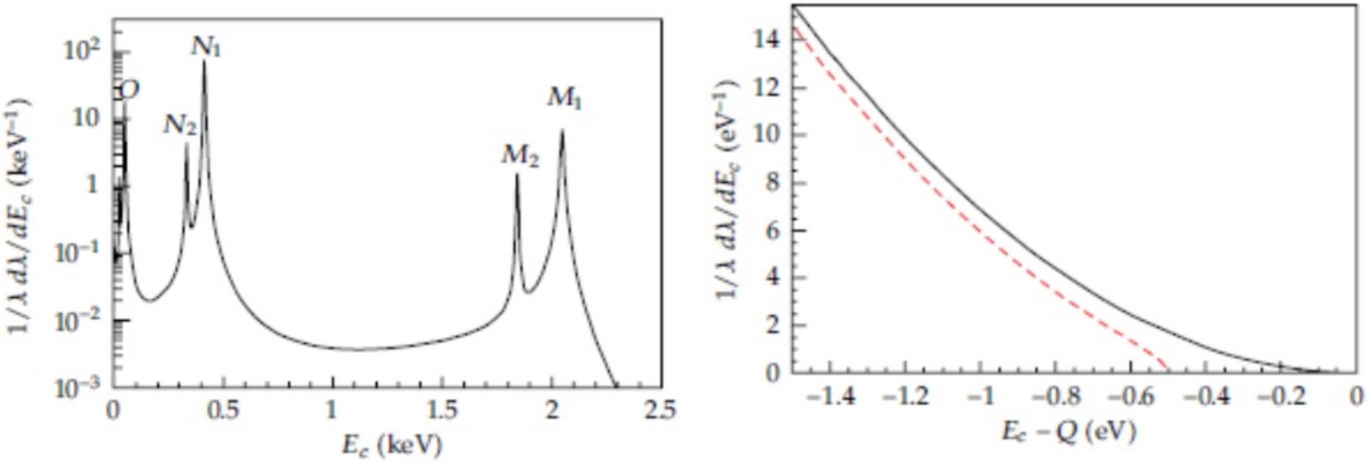
- **MARE**. ^{187}Re and ^{163}Ho efforts towards sub-eV neutrino mass.

Neutrino mass

Direct neutrino mass determination

- Cryobolometers: electron capture (EC) decays of ^{163}Ho





(a) Deexcitation spectrum of ^{163}Ho for Q = 2.5 keV.
(b) zoom into the endpoint region of spectrum with effect of a 0.5 eV neutrino mass (red dashed line)

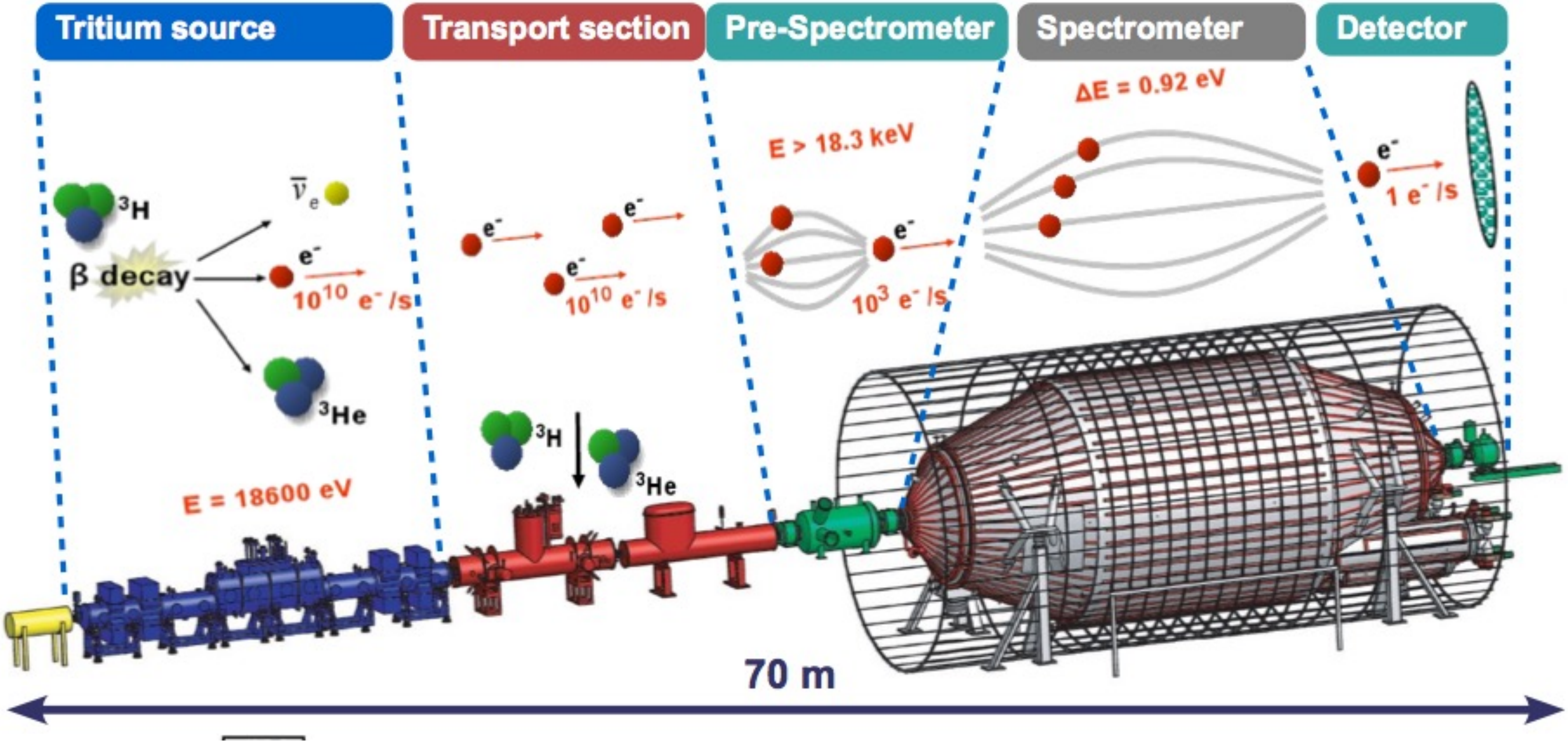
- A promising alternative to β-decay measurements is the study of electron capture (EC) decays of ^{163}Ho to measure the neutrino mass. The considered decay process is

$$^{163}\mathrm{Ho}^{+} + e^{-} \rightarrow {}^{163}\mathrm{Dy}^{*}_{i} + \nu_e \rightarrow {}^{163}\mathrm{Dy} + E_i + \nu_e$$

- The deexcitation spectrum of the intermediate state $^{163}\mathrm{Dy}^{*}_{i}$ is given by a series of lines at energies E_i which correspond to the dissipated binding energy of the electron hole in the final atom. The Q-value of the reaction is given by the mass difference of parent and daughter nucleus in the ground state. Like the electron energy spectrum in β-decays, this spectrum depends on the square of the neutrino mass.
- The use of ^{163}Ho is favored due to its very low Q-Value in the range of 2.3 keV to 2.8 keV.
- By the investigation of the electron capture of ^{163}Ho two upper limits on the average mass of the electron neutrino $m(\nu_e)$ < 225 eV at 95% C.L. and of $m(\nu_e)$ < 490 eV at 68% C.L. were set.

KATRIN

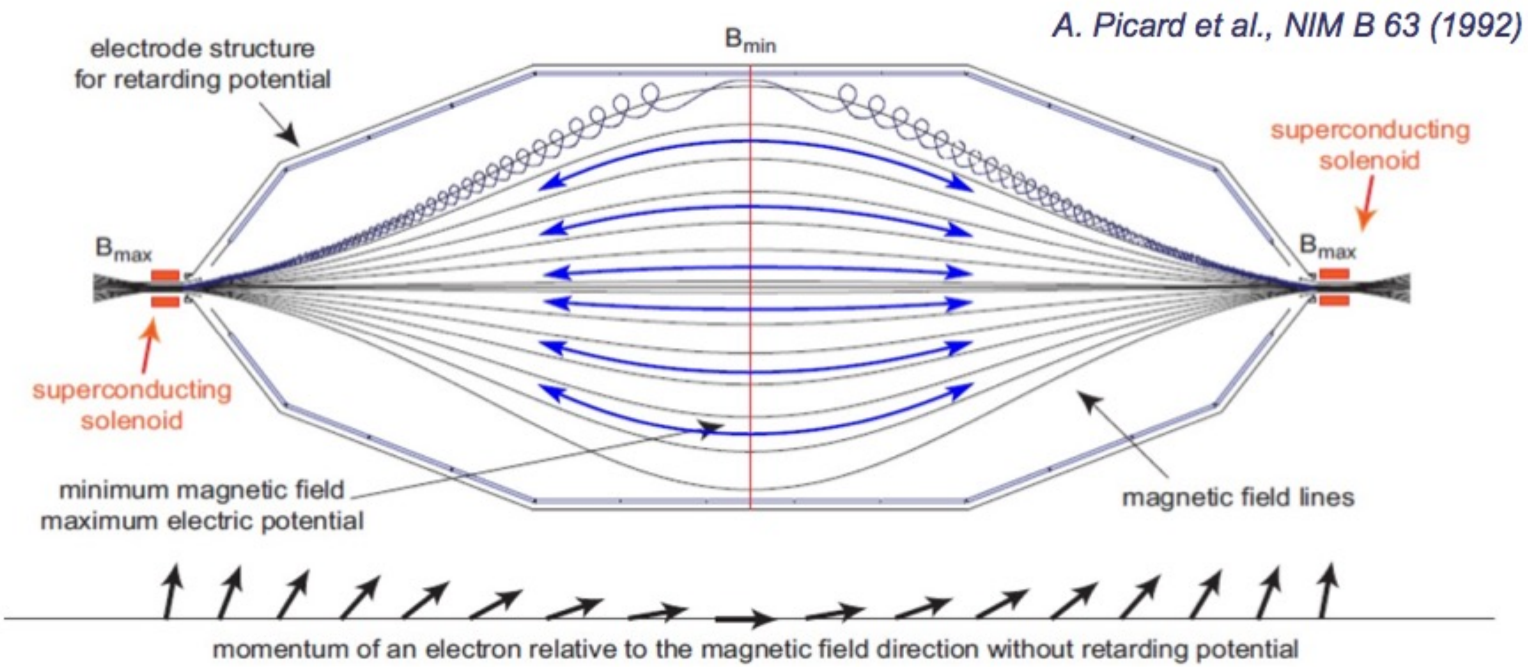
- Experimental site at Karlsruhe
- Tritium beta decay
- Foreseen sensitivity for neutrino mass in 5 years (eff. 3 y of data): **0.2 eV**



KATRIN

MAC-E filter concept

Magnetic Adiabatic Collimation with Electrostatic Filter



A. Picard et al., NIM B 63 (1992)

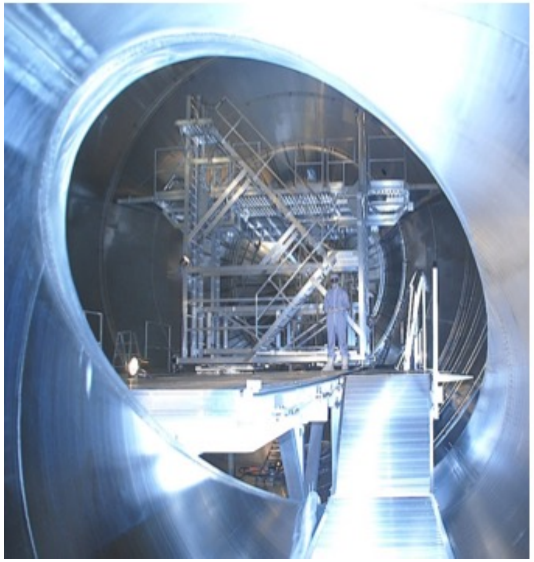
- adiabatic transport → $\mu = E_\perp / B = \text{const.}$
- B drops by $2 \cdot 10^4$ from solenoid to analyzing plane → $E_\perp \rightarrow E_\parallel$
- only electrons with $E_\parallel > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\perp,\text{max, start}} \cdot B_{min} / B_{max} < 1$ eV

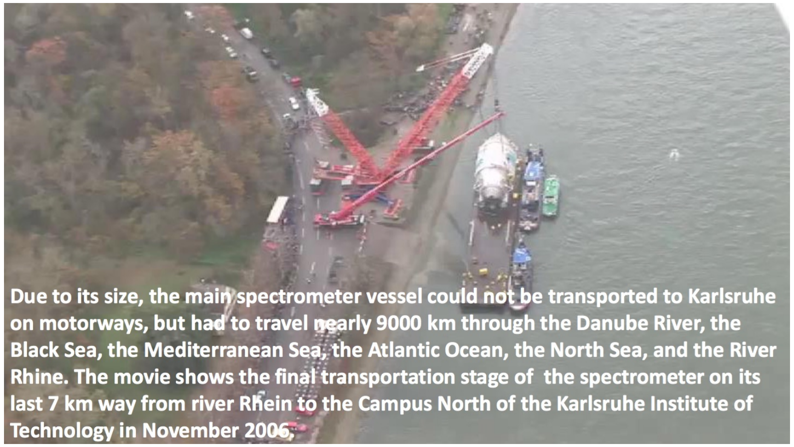
- Electron guided by the B field
- **Large acceptance: 2π**
- Energy of analysis by electric retarding field
- Variable E field (V<30kV at the center)

- Works as high energy pass filter
- **It builds the integral spectrum of electron with energy larger than eV.**
- The B Field transfer transversal impulse in longitudinal one at the center

Main spectr. inner wire electrode

- Purpose: - electrostatic shielding of background electrons
  - shaping of eletric fields
  - removal of trapped particles
- 224 of 248 double layer wire modules installed
- last 24 modules to be installed after preparation of the pump port region in fall 2011
- main spectrometer commissioning spring 2012

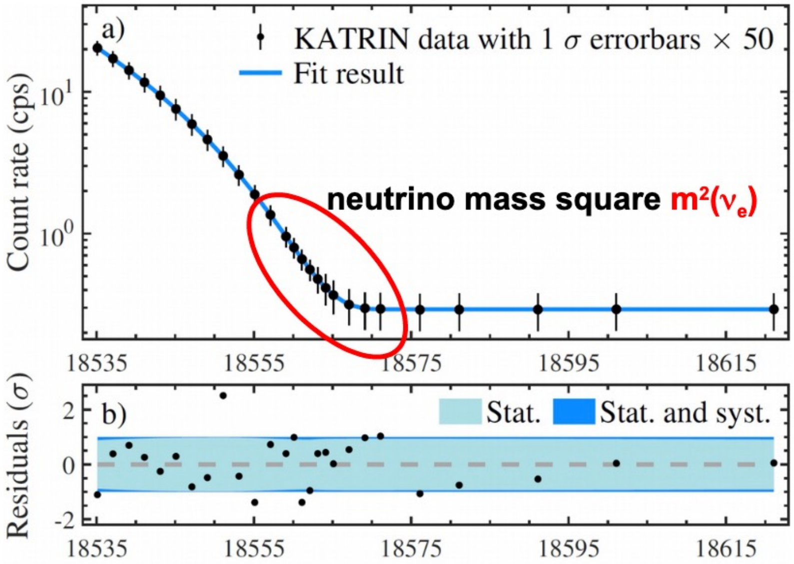


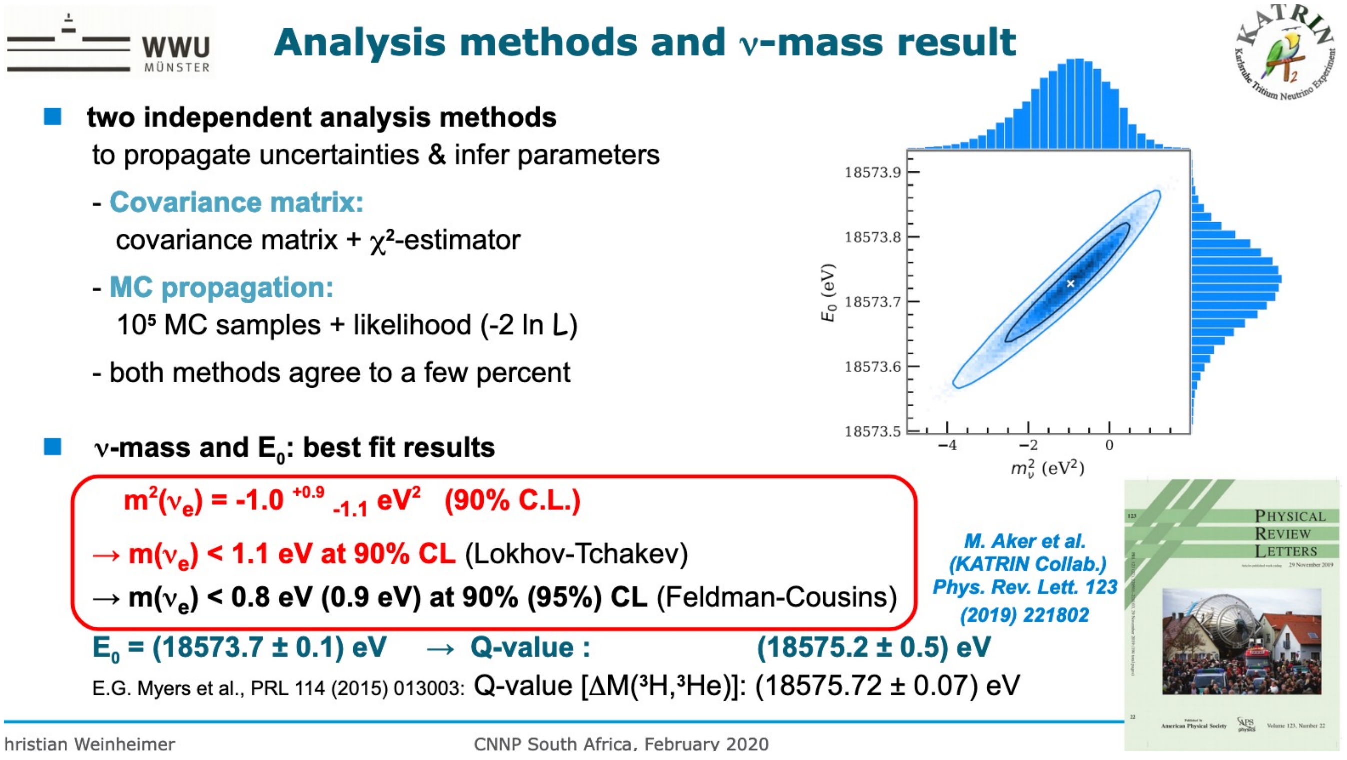


Due to its size, the main spectrometer vessel could not be transported to Karlsruhe on motorways, but had to travel nearly 9000 km through the Danube River, the Black Sea, the Mediterranean Sea, the Atlantic Ocean, the North Sea, and the River Rhine. The movie shows the final transportation stage of the spectrometer on its last 7 km way from river Rhein to the Campus North of the Karlsruhe Institute of Technology in November 2006.

KATRIN results 2020

After corrections for the detector's responses





Analysis methods and ν-mass result

- **two independent analysis methods**
  to propagate uncertainties & infer parameters
  - **Covariance matrix:**
    covariance matrix + χ^2-estimator
  - **MC propagation:**
    10^5 MC samples + likelihood (-2 ln L)
  - both methods agree to a few percent

- **ν-mass and E_0: best fit results**

$m^2(\nu_e) = -1.0\ ^{+0.9}_{-1.1}$ eV² (90% C.L.)

→ $m(\nu_e) < 1.1$ eV at 90% CL (Lokhov-Tchakev)

→ **$m(\nu_e) < 0.8$ eV (0.9 eV) at 90% (95%) CL** (Feldman-Cousins)

E_0 = (18573.7 ± 0.1) eV → Q-value : (18575.2 ± 0.5) eV

E.G. Myers et al., PRL 114 (2015) 013003: Q-value [ΔM(^{3}H,^{3}He)]: (18575.72 ± 0.07) eV

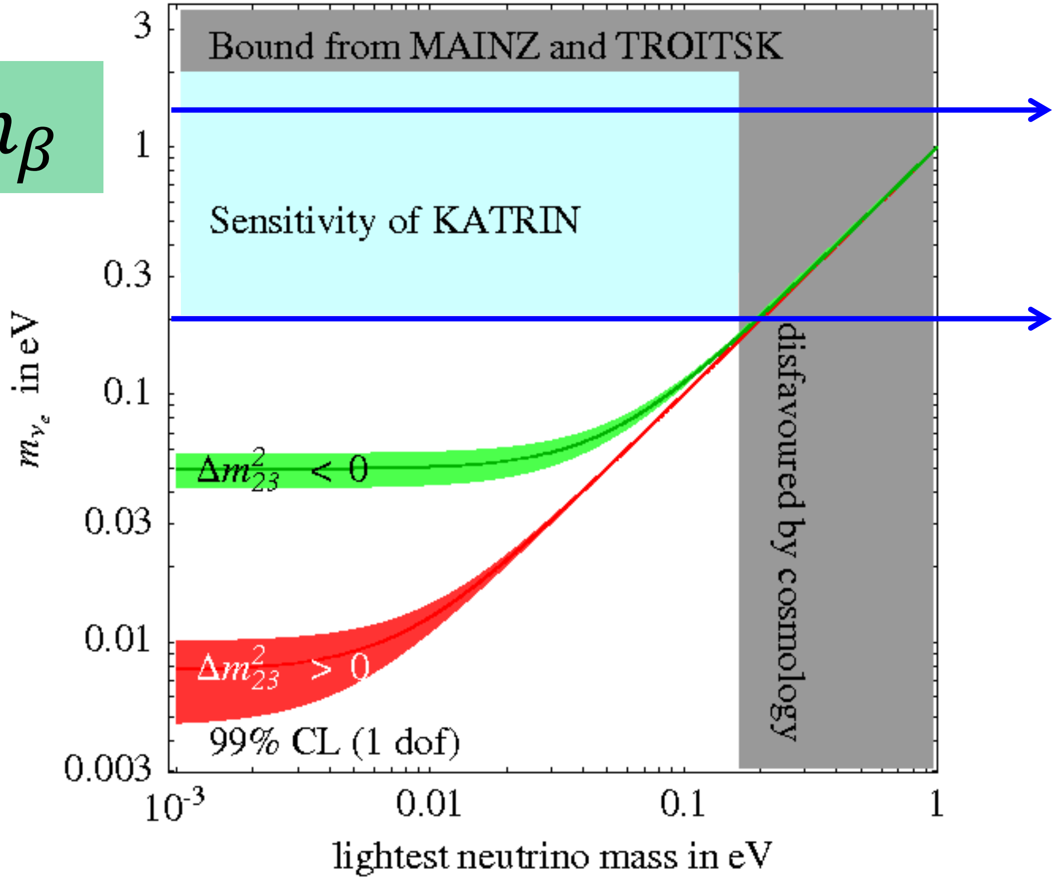
M. Aker et al. (KATRIN Collab.) Phys. Rev. Lett. 123 (2019) 221802

hristian Weinheimer

CNNP South Africa, February 2020

Sensibilità dei futuri esperimenti sulla misura diretta della massa del neutrino (e.g. KATRIN)

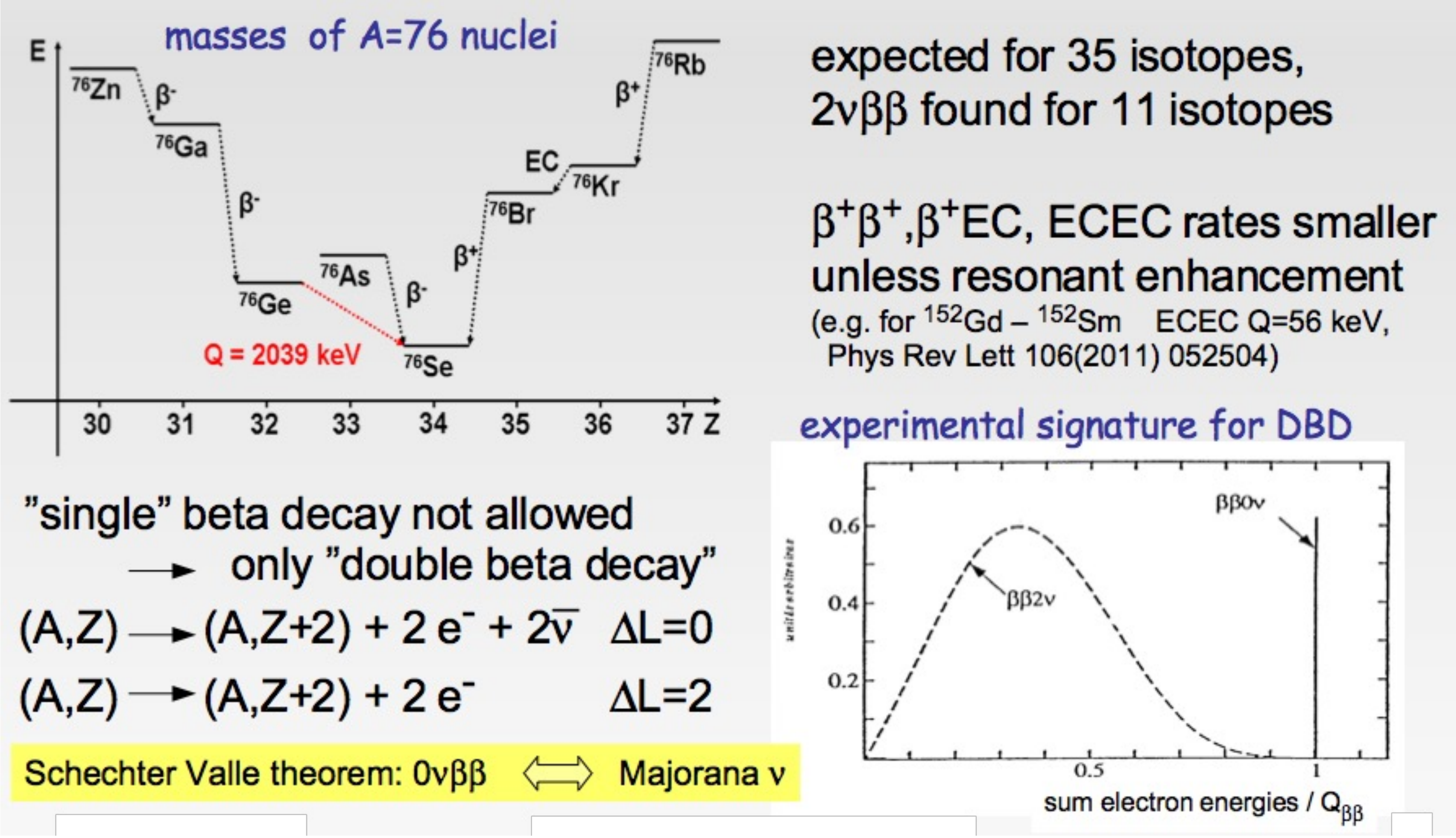
m_β



1.1 eV
(present limit)

0.2 eV
(estimated sensitivity)

Doppio decadimento β



expected for 35 isotopes,
$2\nu\beta\beta$ found for 11 isotopes

$\beta^+\beta^+, \beta^+$EC, ECEC rates smaller unless resonant enhancement
(e.g. for ^{152}Gd – ^{152}Sm ECEC Q=56 keV, Phys Rev Lett 106(2011) 052504)

experimental signature for DBD

"single" beta decay not allowed
→ only "double beta decay"

$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}$ $\Delta L=0$

$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ $\Delta L=2$

Schechter Valle theorem: $0\nu\beta\beta \Longleftrightarrow$ Majorana ν

Dalla **formula di Weizsäcker**

$$M(A,Z) = N\cdot M_n + Z\cdot M_p + Z\cdot m_e - \left(a_v\cdot A - a_s\cdot A^{2/3} - a_c\cdot Z^2\cdot A^{-1/3} + \frac{1}{4}a_a\cdot(N-Z)^2\cdot A^{-1} - \delta\cdot A^{-1/2} \right)$$

$$M(A,Z) = \alpha\cdot A - \beta\cdot Z + \gamma\cdot Z^2 + \delta\cdot A^{-1/2}$$

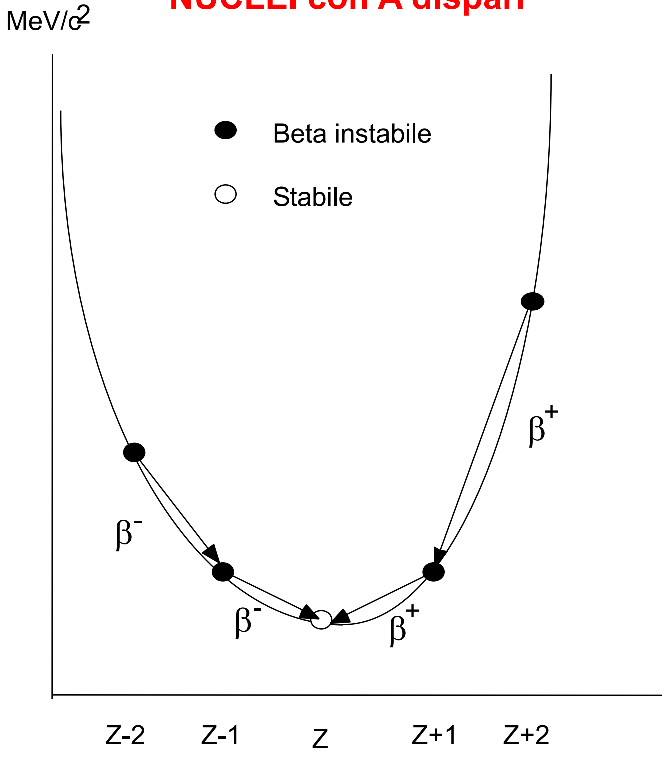
Con

$$\alpha = M_n - a_v + a_s\cdot A^{-1/3} + \frac{1}{4}a_a$$

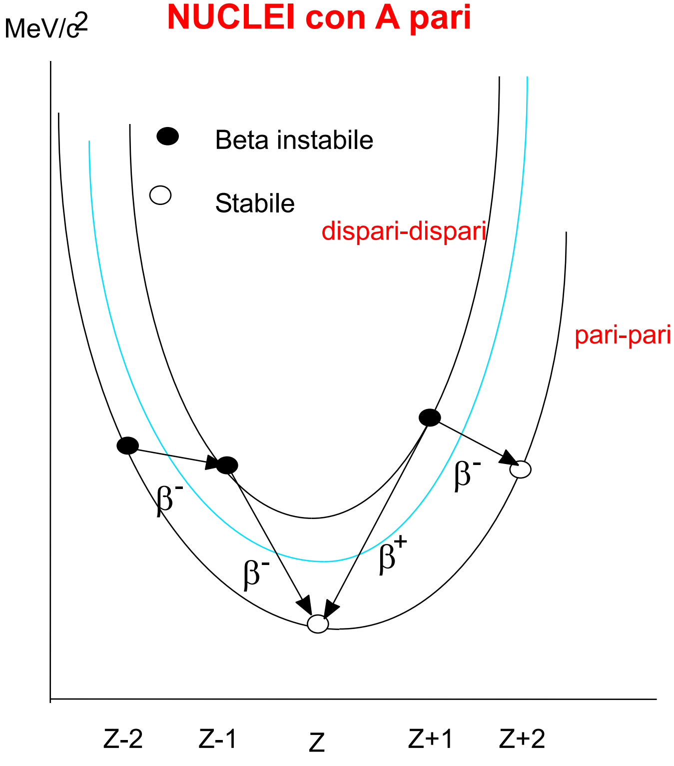
$$\beta = a_a + \left(M_n - M_p - m_e\right)$$

$$\gamma = a_a\cdot A^{-1} + a_c\cdot A^{-1/3}$$

NUCLEI con A dispari

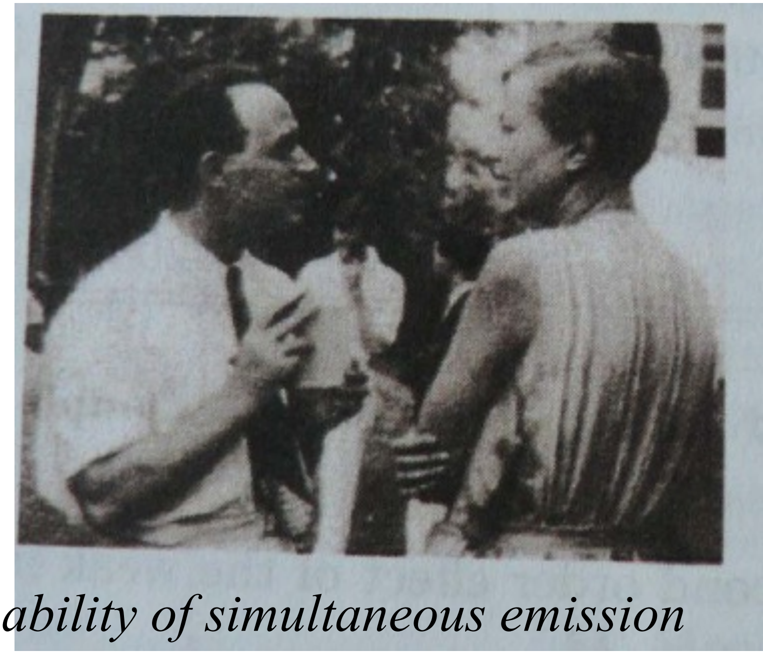


NUCLEI con A pari



ββ –Disintegration

Suggested in general form by **Maria Goepper Mayer** just one year after the Fermi theory of beta decay.



M.Goeppert-Mayer, *The John Hopkins University*
(Received May, 20 , 1935)

*From the Fermi theory of β– disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs **sufficiently rarely** to allow **a half-life of over*** 10^{17} *years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass*

In 1935, Maria Goeppert-Mayer predicted the existence of the 2νββ decay process, allowed in the SM framework. Double beta decay (2νββ) is a nuclear transition in which an initial nucleus (Z,A) decays to (Z+2,A) emitting two electrons and two antineutrinos. This transition occurs regardless of whether neutrinos are their own antiparticles or not, i.e. Majorana or Dirac. 2νββ has been observed in a number of experiments.

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+2}Y + 2e^{-} + 2\bar{\nu}_{e} \quad (Q_{\beta\beta}) $$

Note: $\beta^{+}\beta^{+}$ decay exists too...

Decay modes for Double Beta Decay (DBD)

①

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

$(A,Z) \rightarrow (A,Z-2) + 2e^+ + 2\nu_e$

$(A,Z) + e_a \rightarrow (A,Z-2) + e^+ + 2\nu_e$

$(A,Z) + 2e_a \rightarrow (A,Z-2) + 2\nu_e$

2ν Double Beta Decay (2νββ)
allowed by the Standard Model
already observed – τ ~10^{18} – 10^{21} yr

---

②

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

$(A,Z) \rightarrow (A,Z-2) + 2e^+$

$(A,Z) + e_a \rightarrow (A,Z-2) + e^+$

$(A,Z) + 2e_a \rightarrow (A,Z-2) + \gamma$

neutrinoless Double Beta Decay (0νββ)
never observed except
Klapdor's meas. - τ ~ 10^{25} yr

---

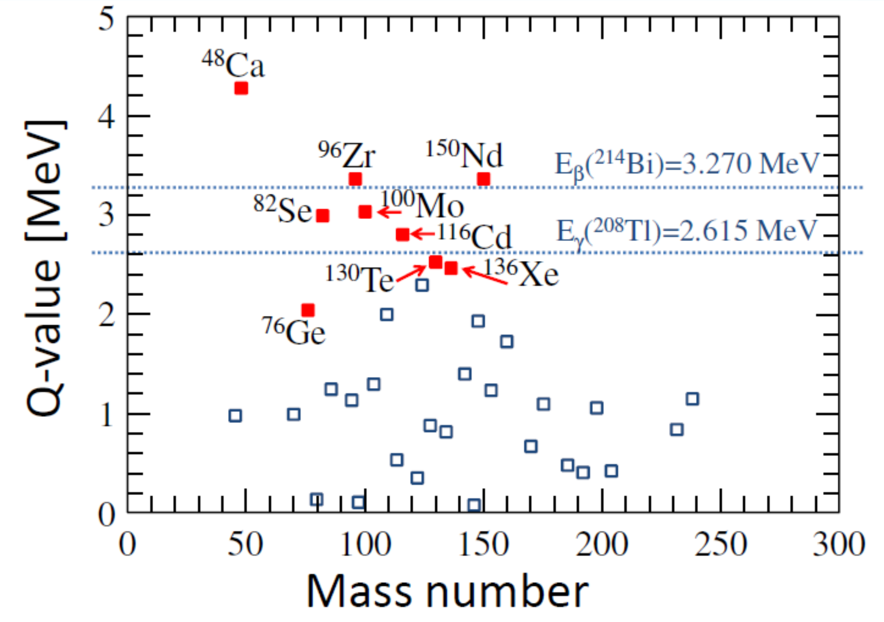
③

0νββ with Majoron
(light neutral boson)
never observed – τ > 10^{22} y

Processes ② and ③ would imply new physics
beyond the Standard Model
violation of total lepton number conservation

How many candidate nuclei?

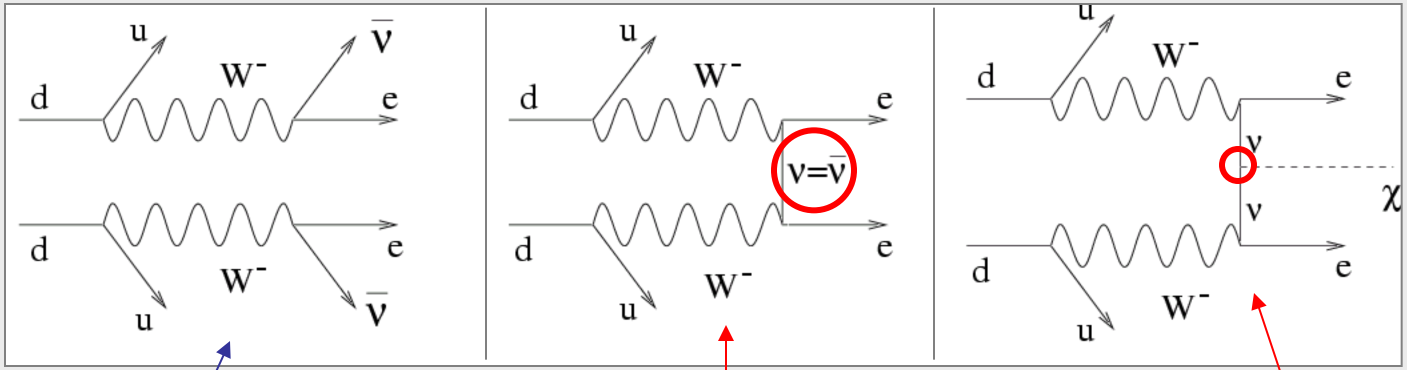
Case of 2β⁻ processes →



Double Beta Decay and neutrino physics

DBD is a second order weak transition ← very low rates

Diagrams for the three processes discussed above:

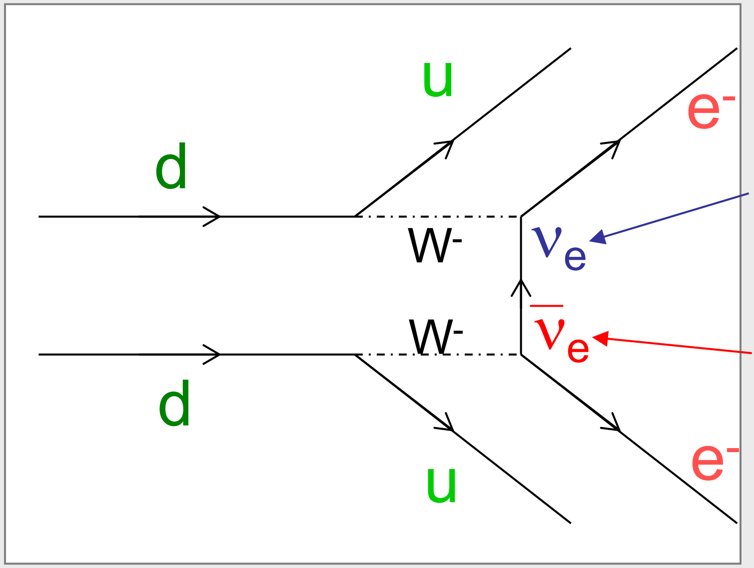


Standard process
two “simultaneous” beta decays

0ν-DBD
a virtual neutrino is exchanged
between the two electroweak lepton vertices

DBD with Majoron emission
A Majoron couples to the
exchanged virtual neutrino

Neutrino properties and 0ν-DBD



a LH neutrino (L=-1)
is absorbed at this vertex

a RH antineutrino (L=1)
is emitted at this vertex

in pre-oscillations
standard particle physics
(massless neutrinos),
the process is forbidden because
neutrino has not the correct
helicity / lepton number
to be absorbed
at the second vertex

- IF neutrinos are massive DIRAC particles:

  Helicities can be accommodated thanks to the finite mass,
  BUT Lepton number is rigorously conserved

  ⇒ **0ν-DBD is forbidden**

- IF neutrinos are massive MAJORANA particles:

  Helicities can be accommodated thanks to the finite mass,
  AND Lepton number is not relevant

  ⇒ **0ν-DBD is allowed**

Observation of **0ν-DBD** ⇒ $m_\nu \neq 0$, $\bar{\nu} \equiv \nu$

DBD and Majorana neutrinos

Schechter Valle theorem: Observation of **0ν-DBD** $\longrightarrow$ $\left\{ m_\nu \neq 0,\ \nu \equiv \bar{\nu} \right\}$ **Majorana particle**

Neutrinoless ββ decay rate

Phase space

Axial vector coupling constant

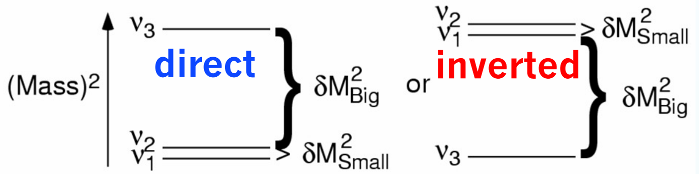
Nuclear matrix elements

Effective **Majorana mass**

$$1/\tau = G(Q,Z)\, g_A^{4}\, |M_{nucl}|^2 \langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha 1}\, |U_{e2}|^2 m_2 + e^{i\alpha 2}\, |U_{e3}|^2 m_3 \right|$$

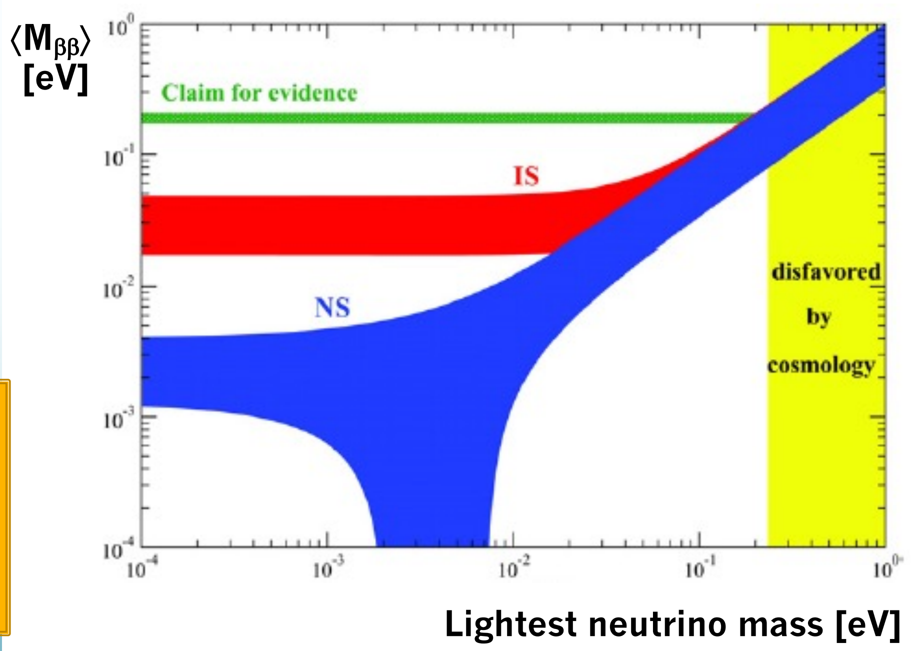
Neutrino mass hierarchy



- This generation of experiments will start to explore the IH region
- Possibly, the next generation will be necessary to complete the IH region exploration
- DH still far from now

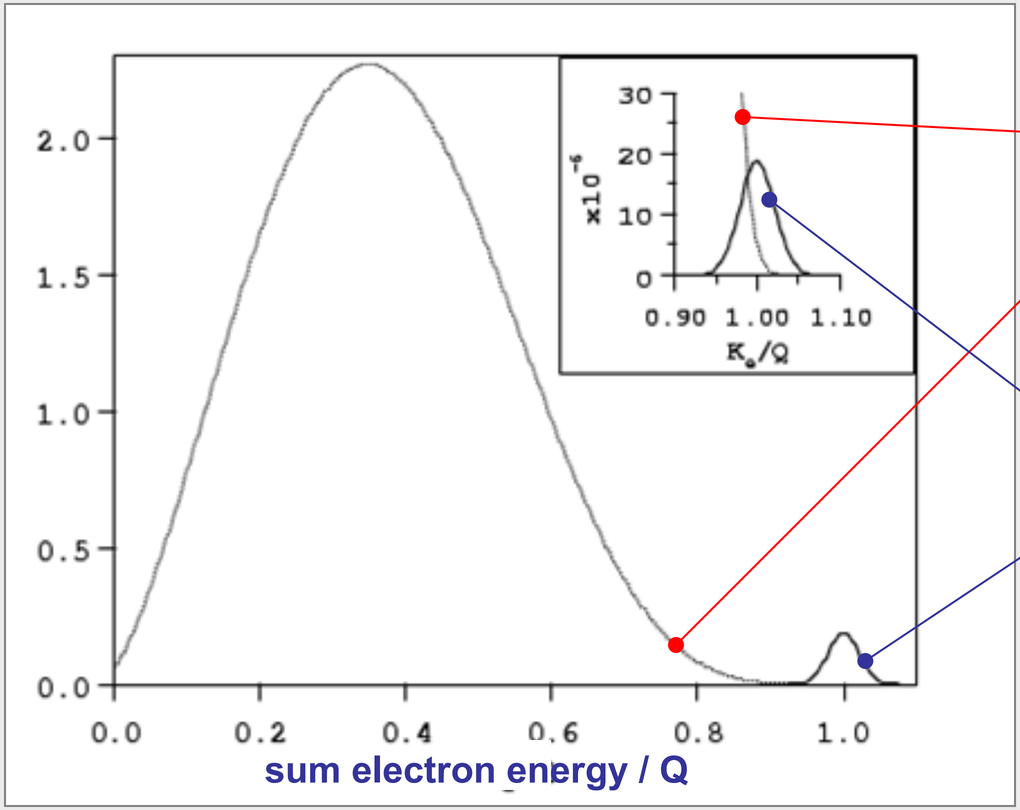
Nuclear matrix elements uncertainties

Needed different nuclei



Electron sum energy spectra in DBD

The shape of the two electron sum energy spectrum enables to distinguish among the three different discussed decay modes



two neutrino DBD
continuum with maximum at ~1/3 Q

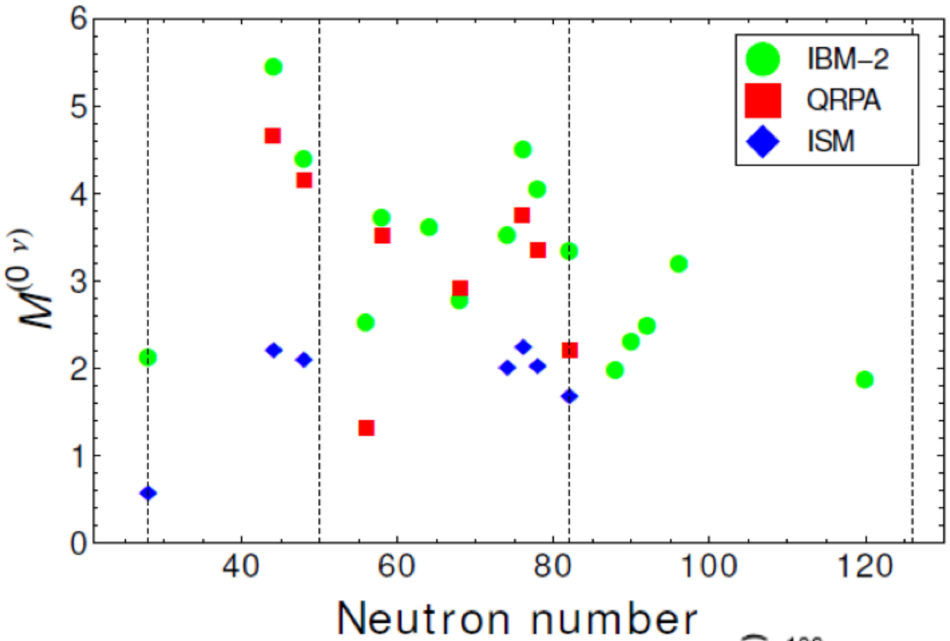
neutrinoless DBD
peak enlarged only by
the detector energy resolution

The Majoron spectrum is a continuum with maximum close to Q
(phase space for a particle decaying to three light objects)

Q ~ 2-3 MeV for the most promising nuclides

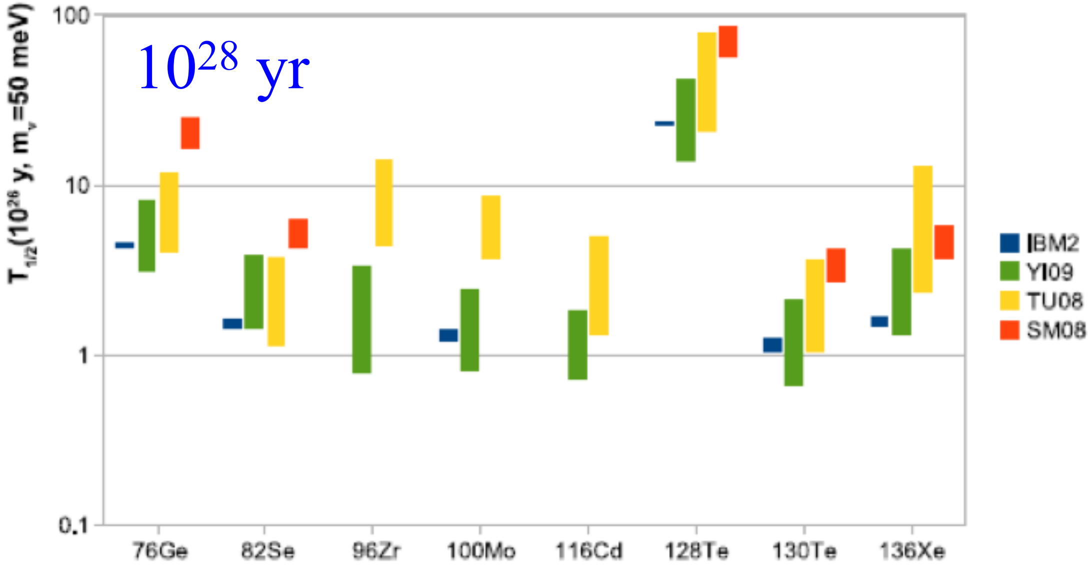
additional signatures:
- single electron energy distribution
- angular distribution

Matrix elements and $T_{1/2}$ expectations



The differences among the nuclear models remain an open question

Expected 0ν2β half-lives for 50 meV effective neutrino mass and different Nuclear Matrix Elements calculations


10^{28} yr

Needed sensitivity for inversed hierarchy

$$\langle m_{ee}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right| = \left||U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_1} m_2 + |U_{e3}|^2 e^{i\alpha_2} m_3\right|$$

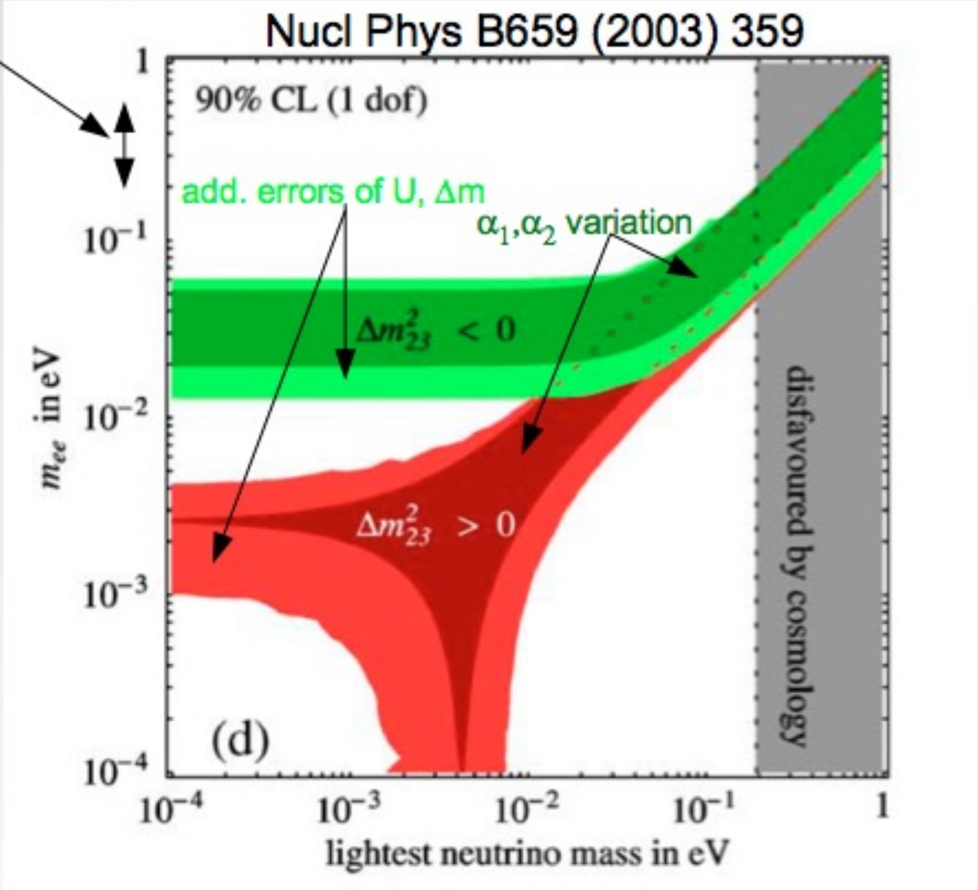
past experiments probe degenerate masses

next and next-to-next generation want to probe inverted mass hierarchy

lower $<m_{ee}>$ is given by (for light ν exchange):

$$\begin{aligned}\langle m_{ee}\rangle^{IH}_{min} = {} & \sqrt{m_3^2+\Delta m_A^2}\cdot\cos(\theta_{12})^2\cdot\cos(\theta_{13})^2 - \\ & \sqrt{m_3^2+\Delta_{sol}^2+\Delta m_A^2}\cdot\sin(\theta_{12})^2\cos(\theta_{13})^2 - \\ & m_3\sin(\delta_{13})^2 \\ \approx {} & (1-2\sin(\theta_{12})^2)\sqrt{\Delta m_A^2} \\ = {} & (0.364^{+0.032}_{-0.038})(49\pm1.2)\ \text{meV} \\ = {} & 17.8^{+1.6}_{-1.9}\ \text{meV}\end{aligned}$$

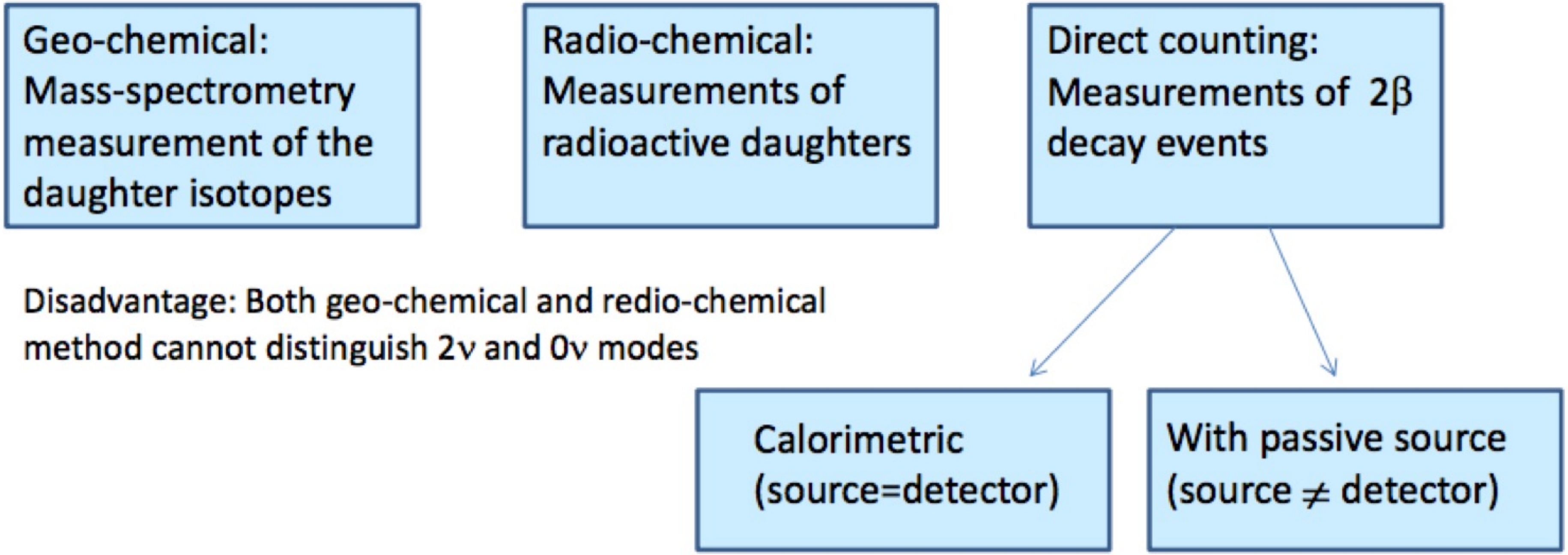
some uncertainty of minimal $<m_{ee}>_{IH}$ given by error on solar mixing (PRD 83 (2011) 113010) for IH experiments need to test 15 meV scale


Nucl Phys B659 (2003) 359

double beta decay

experiments

Approaches to investigate 2β decay



Geo-chemical:
Mass-spectrometry measurement of the daughter isotopes

Radio-chemical:
Measurements of radioactive daughters

Direct counting:
Measurements of 2β decay events

Disadvantage: Both geo-chemical and redio-chemical method cannot distinguish 2ν and 0ν modes

Calorimetric
(source=detector)

With passive source
(source ≠ detector)

Calorimetric approach has certain advantage : no energy losses in source and high detection efficiency. Source ≠ detector approach is promising for 2ν measurements

double beta decay

experiments

Approaches to search for 2β decay: radio-chemical experiment with ^{238}U

Radio-chemical experiment to search for 2β decay of ^{238}U was performed by measuring of the amount of plutonium that had accumulated in 33 yr from 8.47 kg of purified uranyl nitrate. Other sources of ^{238}Pu have been studied and found negligible.

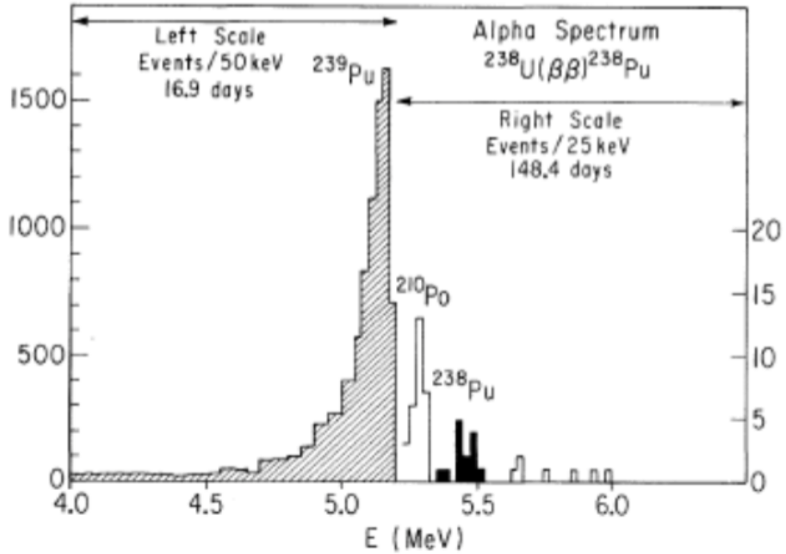


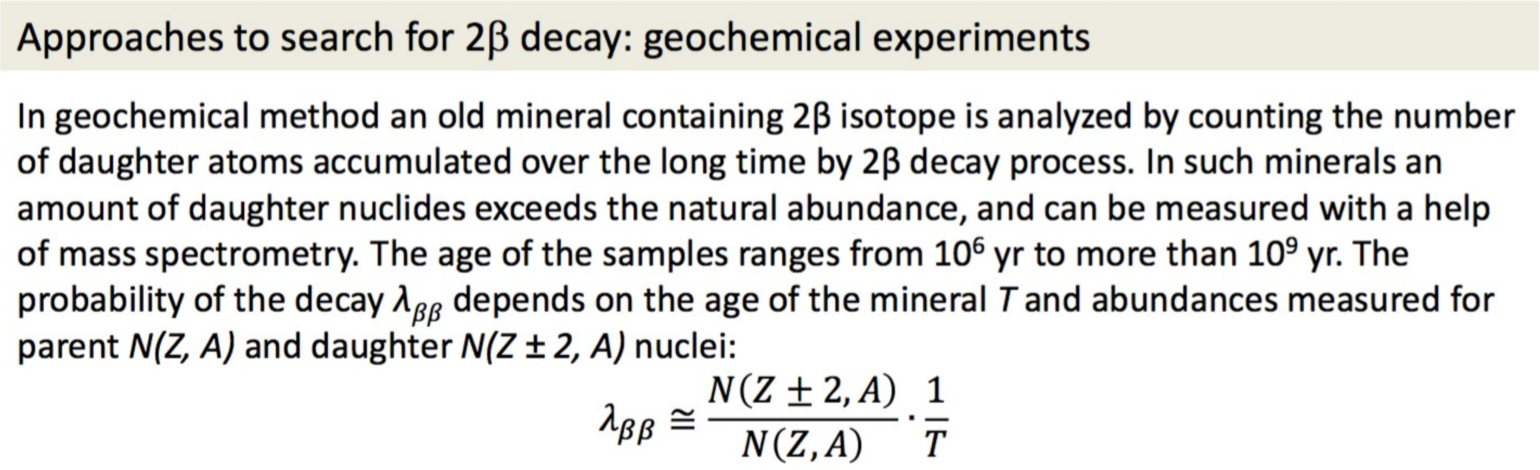
FIG. 1. A sample of the results from experiment A-5 on the University of Chicago counter MCA1 on the production of ^{238}Pu from ^{238}U. Shown are the numbers of alpha particles as a function of energy.

$$T_{1/2}\,(^{238}\mathrm{U}) = (2.0 \pm 0.6) \times 10^{21}\ \mathrm{yr}$$

No possibility to determine mode of decay (0ν or 2ν) despite some speculations using theoretical calculations of 2ν decay contribution

A.L. Turkevich, T.E. Economou, G.A. Cowan, *Double beta decay of ^{238}U.* Phys. Rev. Lett. 67 (1991) 3211–3214.

DBD: geochemical expts

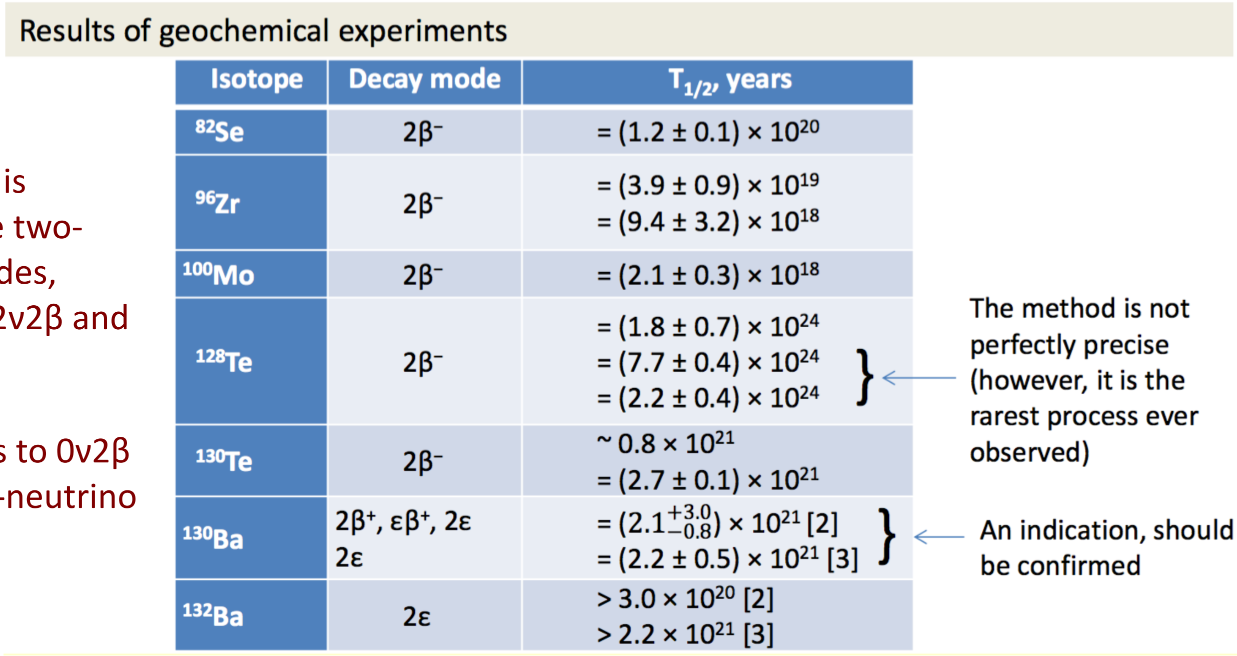


Approaches to search for 2β decay: geochemical experiments

In geochemical method an old mineral containing 2β isotope is analyzed by counting the number of daughter atoms accumulated over the long time by 2β decay process. In such minerals an amount of daughter nuclides exceeds the natural abundance, and can be measured with a help of mass spectrometry. The age of the samples ranges from 10^6 yr to more than 10^9 yr. The probability of the decay $\lambda_{\beta\beta}$ depends on the age of the mineral *T* and abundances measured for parent *N(Z, A)* and daughter *N(Z ± 2, A)* nuclei:

$$\lambda_{\beta\beta} \cong \frac{N(Z\pm 2, A)}{N(Z, A)} \cdot \frac{1}{T}$$

Geochemical experiments are very sensitive mainly in cases when daughter elements are noble gases (^{82}Se → ^{82}Kr, ^{128}Te → ^{128}Xe, ^{130}Te → ^{130}Xe). Why?



Results of geochemical experiments

Isotope	Decay mode	$T_{1/2}$, years
^{82}Se	$2\beta^-$	$= (1.2 \pm 0.1) \times 10^{20}$
^{96}Zr	$2\beta^-$	$= (3.9 \pm 0.9) \times 10^{19}$ $= (9.4 \pm 3.2) \times 10^{18}$
^{100}Mo	$2\beta^-$	$= (2.1 \pm 0.3) \times 10^{18}$
^{128}Te	$2\beta^-$	$= (1.8 \pm 0.7) \times 10^{24}$ $= (7.7 \pm 0.4) \times 10^{24}$ $= (2.2 \pm 0.4) \times 10^{24}$
^{130}Te	$2\beta^-$	$\sim 0.8 \times 10^{21}$ $= (2.7 \pm 0.1) \times 10^{21}$
^{130}Ba	$2\beta^+$, $\varepsilon\beta^+$, 2ε	$= (2.1^{+3.0}_{-0.8}) \times 10^{21}$ [2] $= (2.2 \pm 0.5) \times 10^{21}$ [3]
^{132}Ba	2ε	$> 3.0 \times 10^{20}$ [2] $> 2.2 \times 10^{21}$ [3]

The method is not perfectly precise (however, it is the rarest process ever observed)

An indication, should be confirmed

The main disadvantage of such method is impossibility to distinguish between the two-neutrino and neutrinoless 2β decay modes, therefore $\lambda_{\beta\beta}$ is the total probability of 2v2β and 0v2β decay modes:
$\lambda_{\beta\beta} = \lambda_{2\nu} + \lambda_{0\nu}$.
Thus the sensitivity of such experiments to 0v2β process is limited by half-life of the two-neutrino 2β decay.

Direct counting: measurement of 2β decay events

- ❑ calorimetric (source = detector)
- ❑ with passive source (source $\neq$ detector)

Background sources

- Natural ra
  (source its
- Neutrons
- Cosmogenic induced a
- 2 ν Double Beta Decay

Two main sources

- Activity in the rock and in surrounding materials
  (α, n) processes ⇒ [0,10] MeV spectrum
  ⇒

- Hi
  co
  ⇒
  ⇒
  ⇒ reliable simulations

Choice of materials

Storage of materials underground

Partial or full detector realization underground
(Ge diodes)

ntamination

ish:

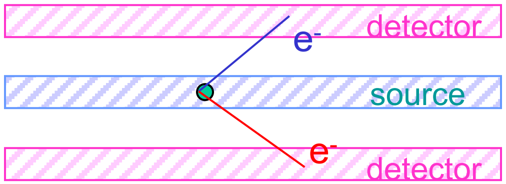
fficient)

Improve alternative techniques:
- ICPMS
- Neutron Activation Analysis
- "Ad hoc" bolometers for alpha self-counting
- Full prototype used to measure contamination
  (BiPo detector)

Experimental approaches to direct searches

Two approaches for the detection of the two electrons:

①



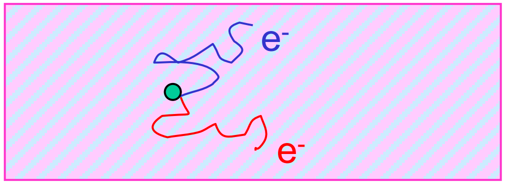
Source ≠ Detector

- scintillation
- gaseous TPC
- gaseous drift chamber with magnetic field and calorimetry

☹ difficulties for large source mass
☺ neat reconstruction of event topology
☺ several candidates with the same detector

Event reconstruction
Low efficiency
Low energy resolution

②



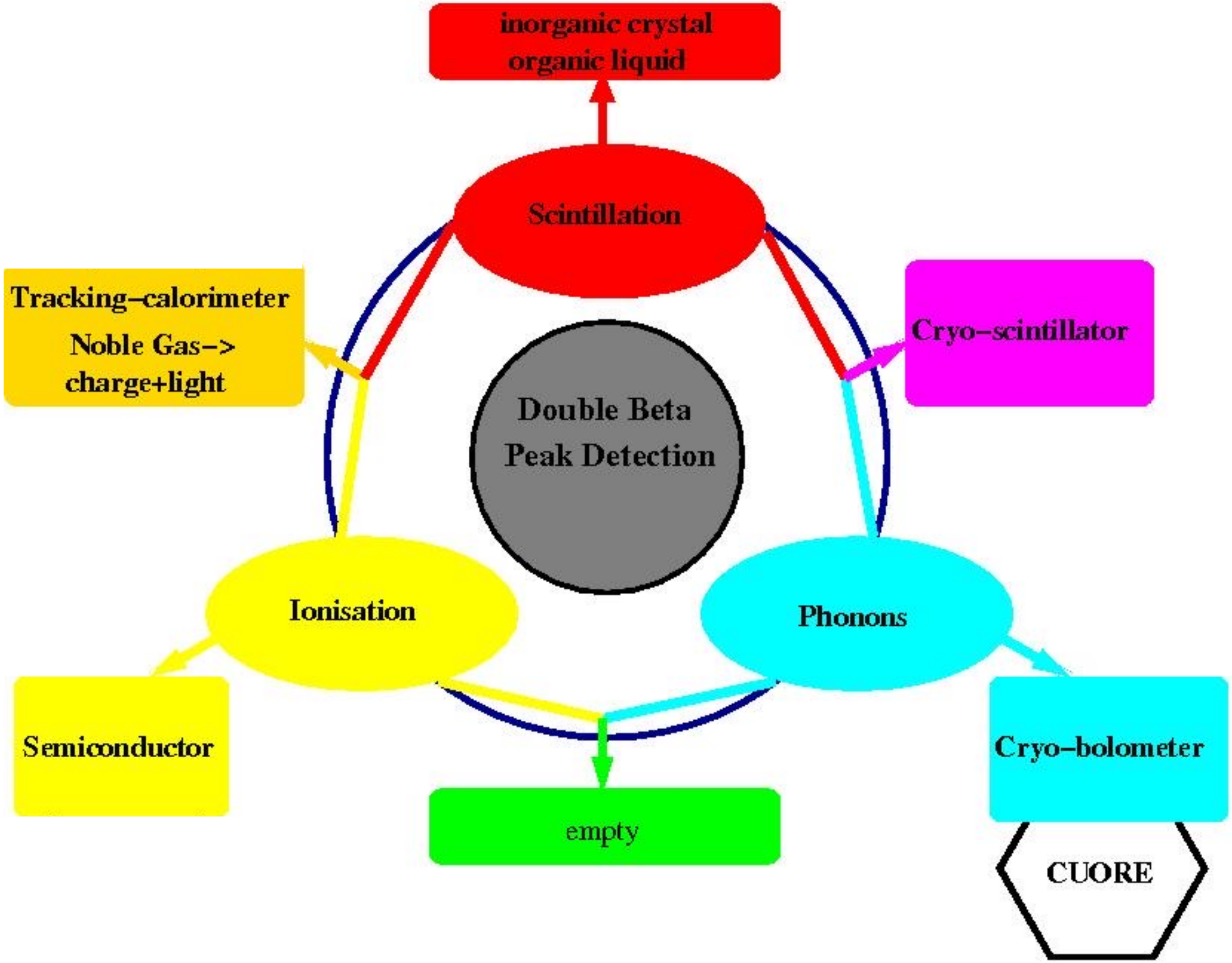
Source ≡ Detector

- scintillation
- solid-state devices
- gaseous, liquid detectors
- cryogenic bolometers

☹ constraints on detector materials
☺ very large masses possible
☺ very high energy resolution
☺ Possible indication of event topology

High efficiency
Energy resolution

Techniques


inorganic crystal
organic liquid
Scintillation
Tracking–calorimeter
Noble Gas–>
charge+light
Cryo–scintillator
Double Beta
Peak Detection
Ionisation
Phonons
Semiconductor
empty
Cryo–bolometer
CUORE

Experimental sensitivity

$N^{0\nu} = \frac{N_T}{\tau} t\varepsilon;$ sapendo che: $N_T = \frac{MN_A}{A} a$ $\tau = T_{1/2} / \ln 2$

Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot Mt / T_{1/2}$ and $N^{bkg} = Mt \cdot B \cdot \Delta E$

Experimental sensitivity

$$T_{1/2}(90\% CL) > \begin{cases} \frac{\ln 2}{2.3} \frac{N_A}{A} a \cdot \epsilon \cdot Mt & \text{for } N^{bkg} = 0 \\ \frac{\ln 2}{1.64} \frac{N_A}{A} a \cdot \epsilon \sqrt{\frac{Mt}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

$N^{0\nu} < 2.3$ (90% CL)

$N^{0\nu} < 1.64\sqrt{MtB\Delta E}$

(90% CL)

$$T_{1/2} = \ln 2 \frac{N_A}{A} a\varepsilon Mt \frac{1}{N^{0\nu}}$$

M = mass of the element in the detector

t = measurement time

A = isotope mass per mole

N_A = Avogadro constant

a = fraction of 0νββ isotope

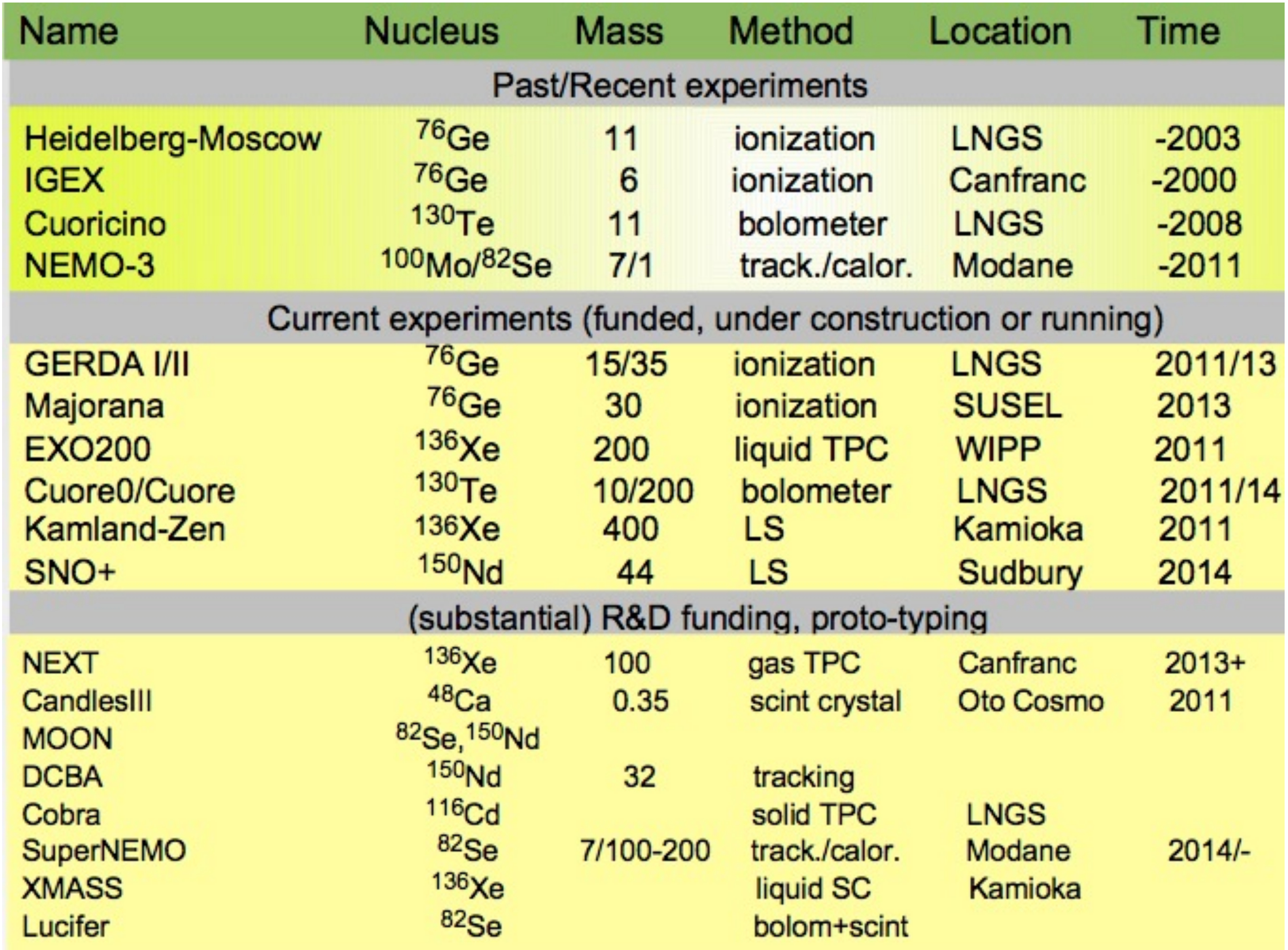
ε = detection efficiency

B = background index in units cnt/(keV kg y)

ΔE = energy resolution = energy window size

Experimental overview

ββ0ν-decay Projects



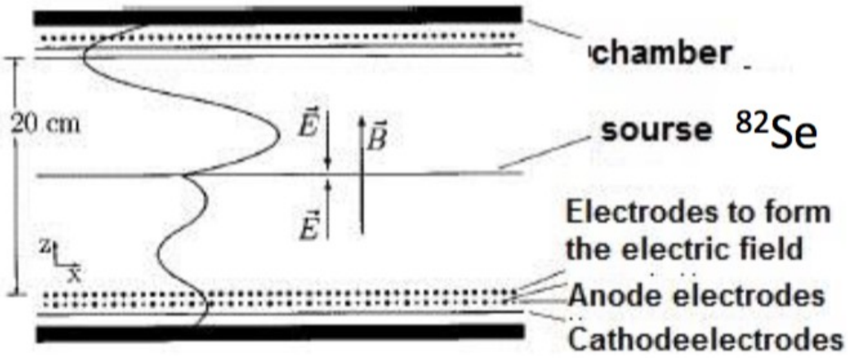
Name	Nucleus	Mass	Method	Location	Time
Past/Recent experiments					
Heidelberg-Moscow	^{76}Ge	11	ionization	LNGS	-2003
IGEX	^{76}Ge	6	ionization	Canfranc	-2000
Cuoricino	^{130}Te	11	bolometer	LNGS	-2008
NEMO-3	^{100}Mo/^{82}Se	7/1	track./calor.	Modane	-2011
Current experiments (funded, under construction or running)					
GERDA I/II	^{76}Ge	15/35	ionization	LNGS	2011/13
Majorana	^{76}Ge	30	ionization	SUSEL	2013
EXO200	^{136}Xe	200	liquid TPC	WIPP	2011
Cuore0/Cuore	^{130}Te	10/200	bolometer	LNGS	2011/14
Kamland-Zen	^{136}Xe	400	LS	Kamioka	2011
SNO+	^{150}Nd	44	LS	Sudbury	2014
(substantial) R&D funding, proto-typing					
NEXT	^{136}Xe	100	gas TPC	Canfranc	2013+
CandlesIII	^{48}Ca	0.35	scint crystal	Oto Cosmo	2011
MOON	^{82}Se,^{150}Nd				
DCBA	^{150}Nd	32	tracking		
Cobra	^{116}Cd		solid TPC	LNGS	
SuperNEMO	^{82}Se	7/100-200	track./calor.	Modane	2014/-
XMASS	^{136}Xe		liquid SC	Kamioka	
Lucifer	^{82}Se		bolom+scint		

+ Efforts on $\beta^+\beta^+$ … and much more

double beta decay

experiments: first direct detection of 2ν2β decay

TPC to search for 2β decay of ^{82}Se



First counting experiment observed 2ν2β decay of ^{82}Se with $T_{1/2} = 1.1^{+0.8}_{-0.3} \times 10^{20}$ yr [1]

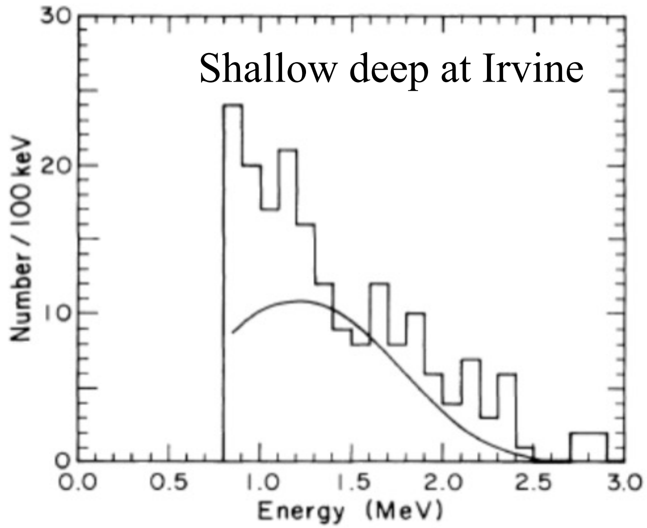


FIG. 1. The observed sum-energy spectrum of two-electron events. A threshold of 800 keV was imposed on the sum energy of the events, and a threshold of 150 keV was imposed on the single energy. The curve is the theoretical $\beta\beta(2\nu)$ sum-energy spectrum normalized to 1.1×10^{20} yr.

- Gas filled volume
- Particles traversing the volume ionize the gas
- Electrons drift towards the anode and cathode electrodes
- Signal is amplified and generates a 2D picture
- Measuring drift time allows the reconstruction of 3rd dimension

[1] S.R. Elliott, A. A. Hahn, and M. K. Moe, *Direct evidence for two-neutrino double-beta decay in* ^{82}*Se*. Physical Review Letters 59 (1987) 2020.

KKDC result

2001 – Evidence for $0\nu\beta\beta$ peak at 2039keV

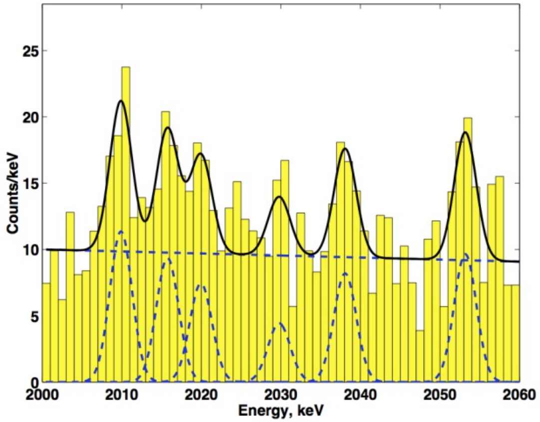
Phys. Lett. B 586 (2004) 198

KKDC used five ^{76}Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data (1990–2003)

0.2% or better energy resolution

$$T_{1/2}^{0\nu}(^{76}Ge) = 2.23^{+0.44}_{-0.31} \times 10^{25}\, y$$

$$0.1 < m_\nu < 0.9 \text{ eV}$$

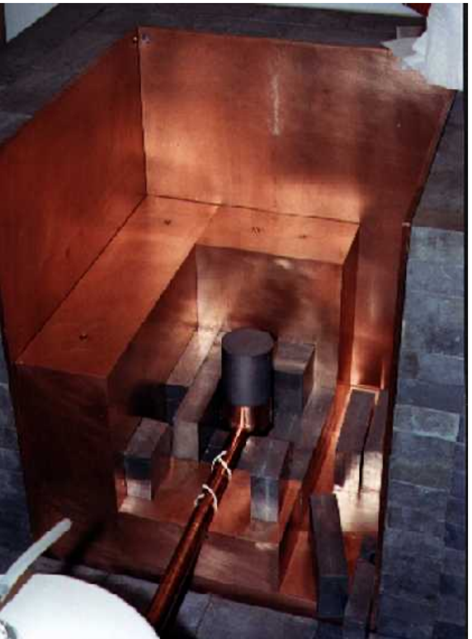


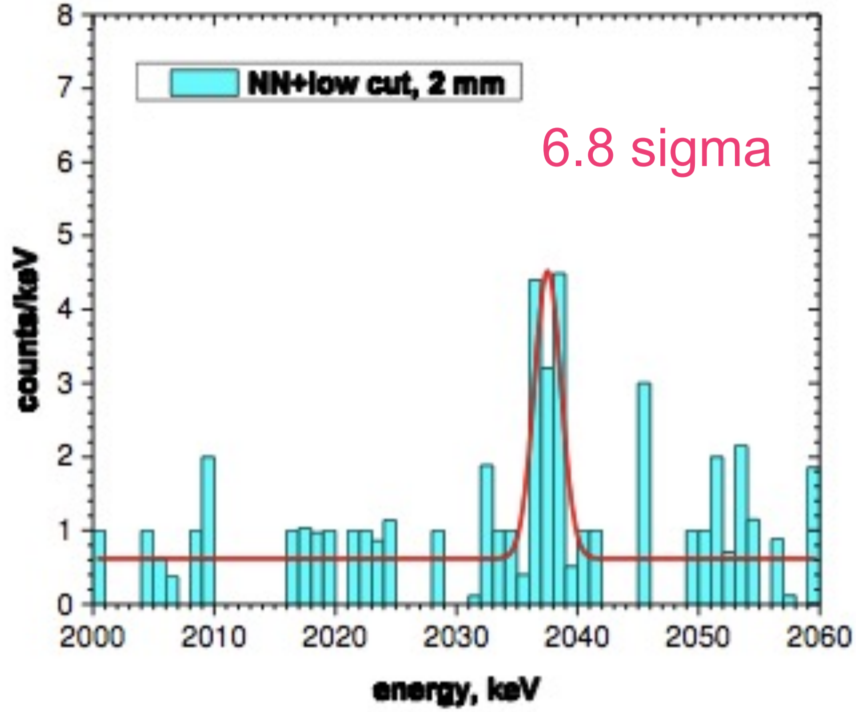
Refined analysis in 2006

Two different methods of pulse shape analysis

neuronal net approach,

selection by a new method comparing measured pulses with a library of pulse shapes of point-like events calculated from simulation of the electric field distribution in the detectors





6.8 sigma

Modern Physics Letters A 21 (2006) 1547

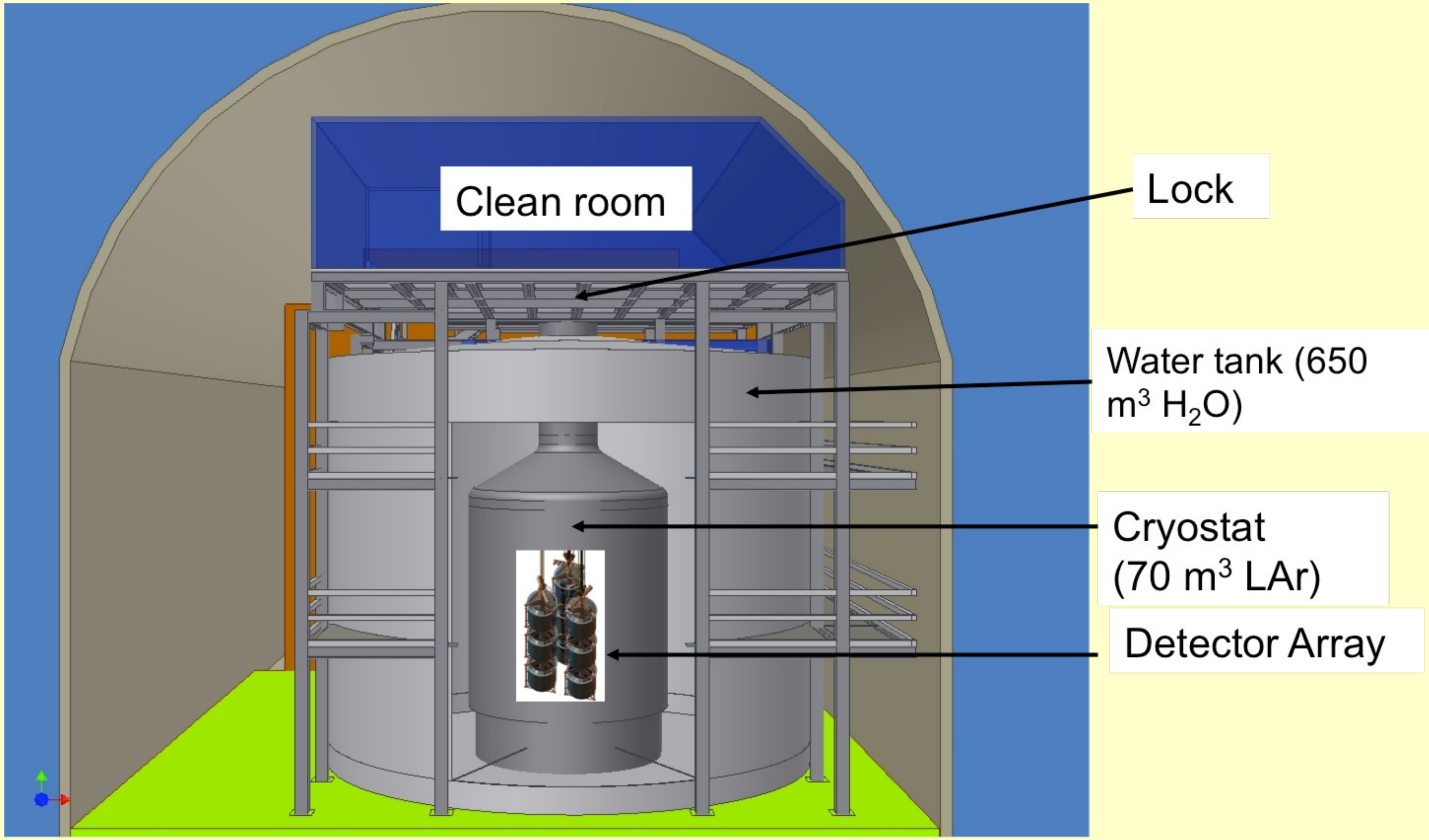
New Germanium Experiments

GERDA

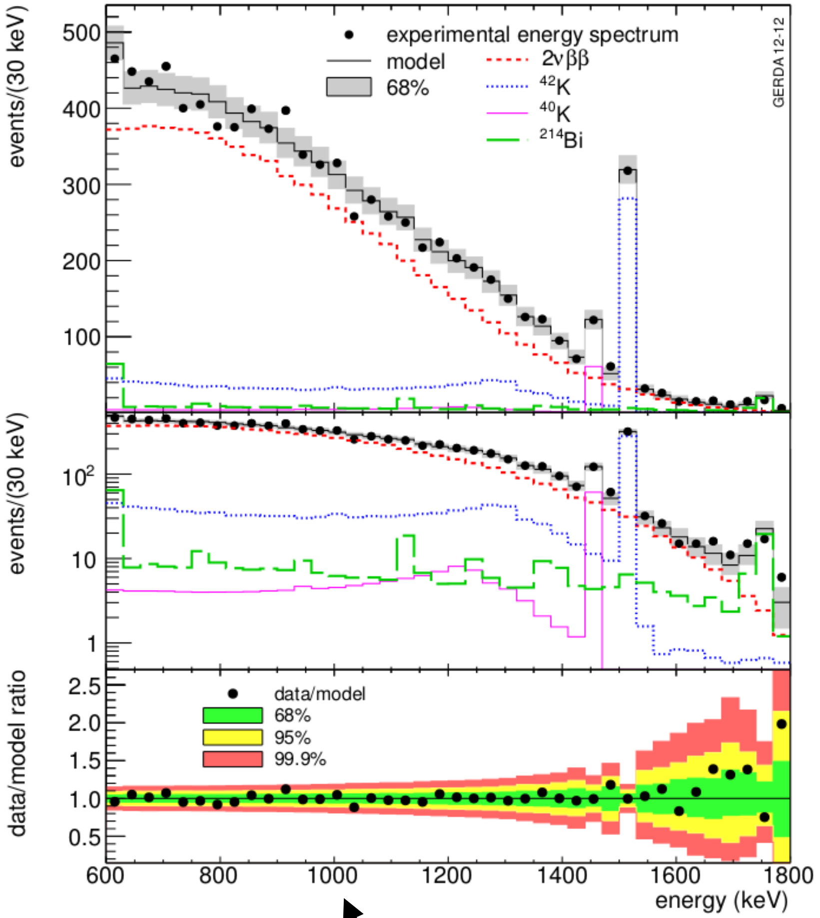
GERDA

- GERmanium Detector Array
- At LNGS

- Germanium Diodes
  - Inherited from HM, IGEX
- Cu cryostat filled with LAr
- 3m thick Čerenkov H_2O shield

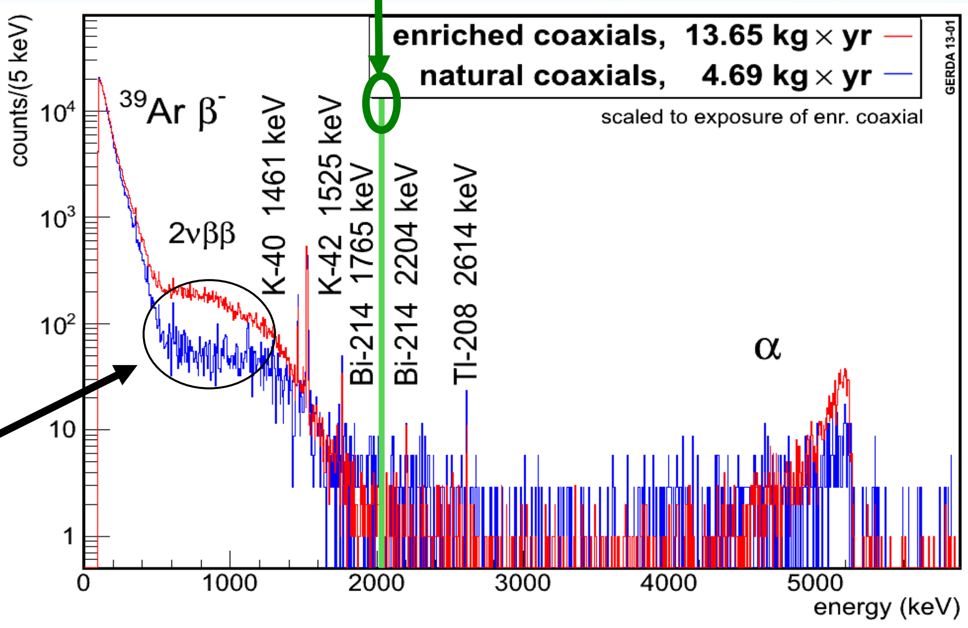


$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08}\ (fit)\ ^{+0.11}_{-006}\ (syst))\times 10^{21}\text{yr}$$



Fondo un fattore ~10 inferiore agli esperimenti di HdM e IGEX

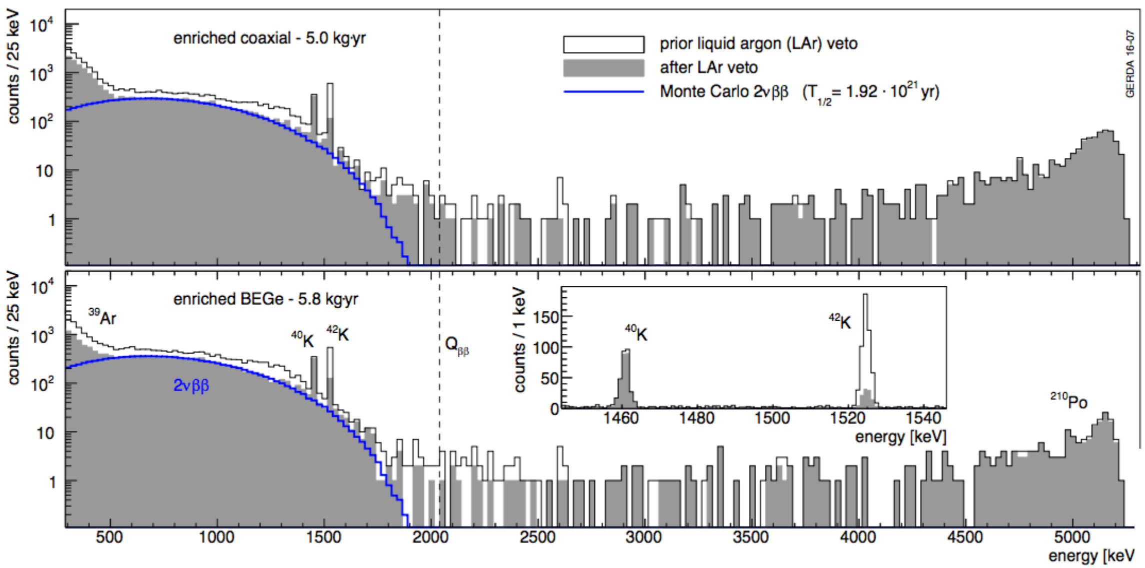
La regione tra 2019 e 2049 keV
è esclusa dalla definzione dei tagli
(blinded analysis)

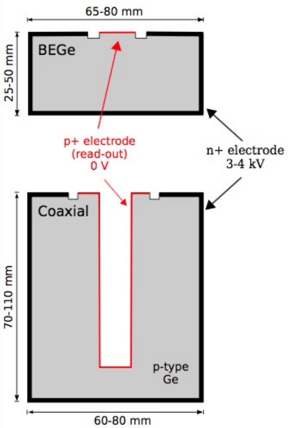


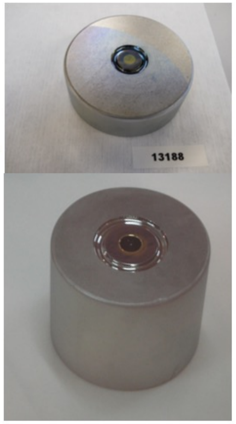
Eventi 2νββ
chiaramente visibili

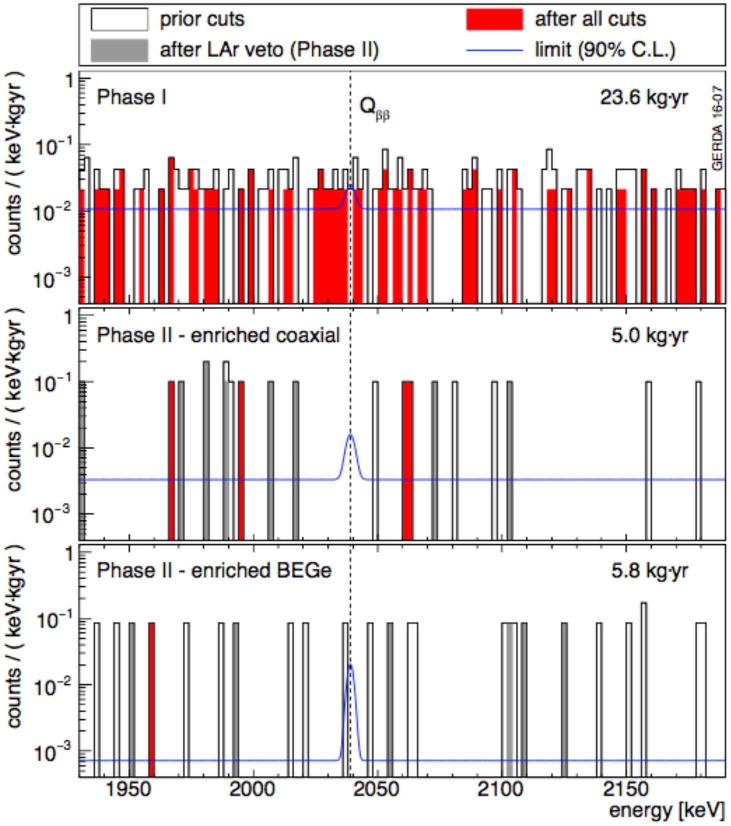
GERDA - Fase II:

arXiv:1703.00570



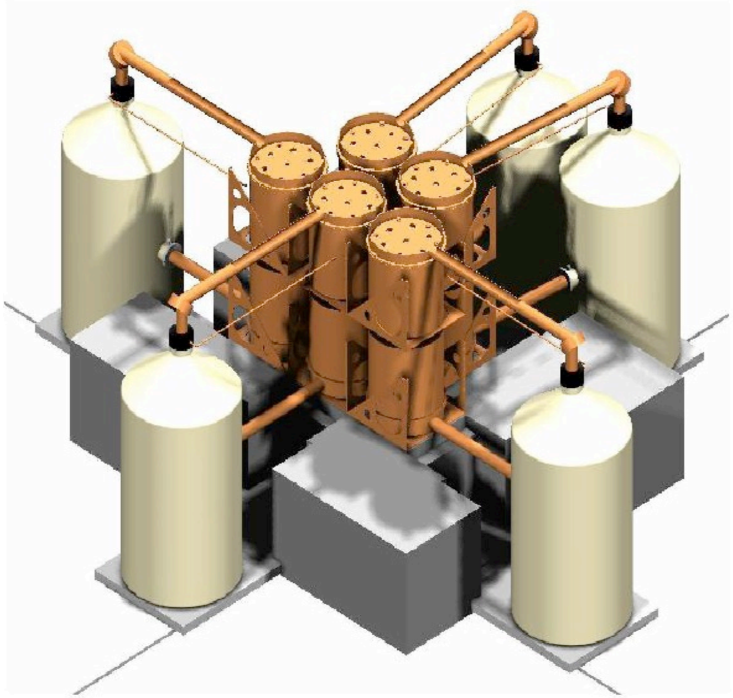






- Background level ≈ 10^{-3} cts/(keV · kg · yr), which is the world-best if weighted by the narrow energy-signal region of germanium detectors.
- Combining Phase I and II data we find no signal and deduce a new lower limit for the half-life of 5.3 × 10^{25} yr at 90 % C.L.
- Sensitivity of 4.0 × 10^{25} yr is competitive with experiments with significantly larger isotope mass.
- For light Majorana neutrino exchange and a nuclear matrix element range for ^{76}Ge between 2.8 and 6.1, the Gerda half-life limit converts to $m_{\beta\beta}$ <0.15–0.33 eV (90% C.L.).
- $T^{2\nu}_{1/2} = (1.926 \pm 0.094) \cdot 10^{21}$ yr

Majorana



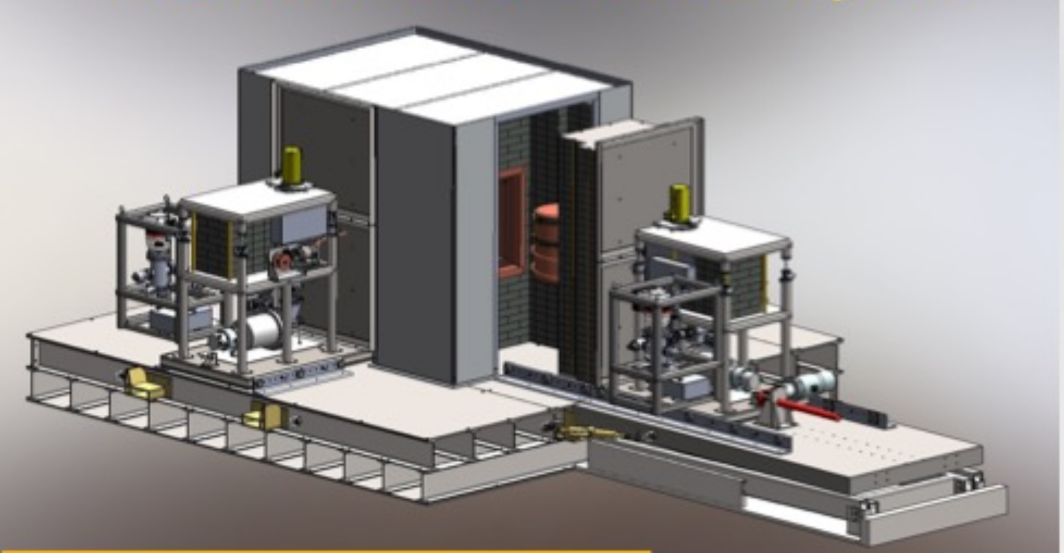
- 500kg enriched Ge
  Segmented detectors
- Based on IGEX technology
  - background reduced by >50
  - cosmogenic n spallation

- 10 years → $T_{1/2} > 4\ 10^{27}$ years

  $\langle m_\nu \rangle \sim 0.03\text{-}0.04$ eV

Majorana Demonstrator

BEGe detectors in conventional cryostat



19 ^{nat}Ge diodes in hand
working in string

20 kg enriched Ge on its way!

"self-made" electro-formed Cu
as shield: 16 baths in operation!

Next steps:

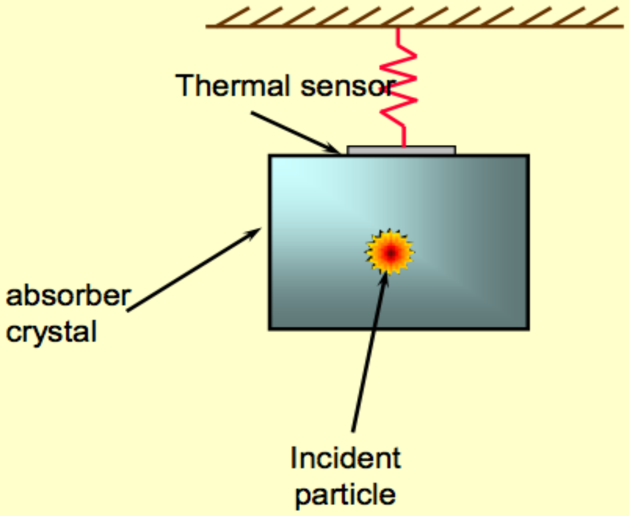
- 2012 first cryostat above ground with ^{nat}Ge detectors
- 2013 below ground with ^{nat}Ge and ^{enr}Ge diodes
- 2014 full experiment
- background level 0.004 cnt/(ROI kg y), ROI ~ 4 keV

background level would be good enough for ton scale exp.

Start data taking in 2016

A new technique => Thermal detectors

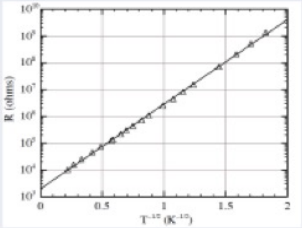
$$\Delta T = \frac{Q}{C_V}$$



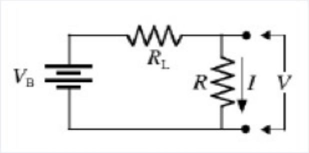
$$C_V = 1944 \frac{V}{V_m} \left(\frac{T}{\Theta}\right)^3 \text{ J/K}$$

Energy resolution	<1 eV	~ 2eV	@ 6 keV
	~10 eV	~keV	@ 2 MeV

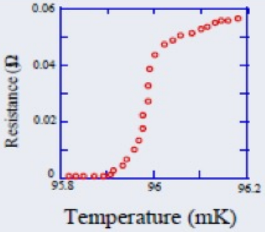
Doped Semiconductors



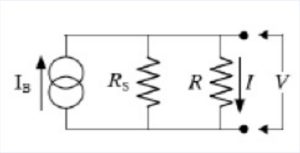
- α negative; $|\alpha| < 10$
- Resistance large
- Current bias and read voltage



Superconducting transition-edge



- α positive; $10 < \alpha < 1000$
- Resistance small
- Voltage bias and read current



IL NUOVO SAGGIATORE

BOLLETTINO DELLA SOCIETÀ ITALIANA DI FISICA

5*1989*1

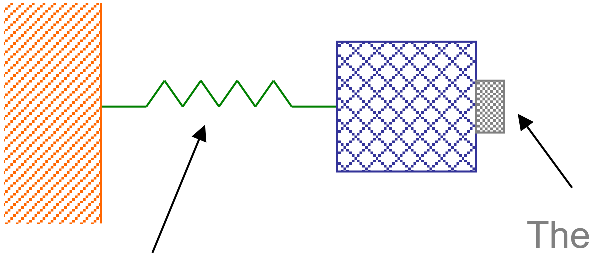
Cuoricino experiment

^{130}Te as a DBD emitter

- high natural isotopic abundance (I.A. = 33.87 %)
- high transition energy (Q = 2530 keV)
- encouraging theoretical calculations for 0ν–DBD lifetime
- already observed with geo-chemical techniques ($T_{1/2\ \mathrm{incl}} = (0.7 - 2.7) \times 10^{21}$ y)
- 2ν DBD decay observed by a precursor bolometric experiment (MIBETA) and by NEMO3 at the level $T_{1/2} = (5 - 7) \times 10^{20}$ y

$\langle M_{\beta\beta}\rangle \approx 50$ meV ⇔ $\tau \approx 2\times10^{26}$ y

The bolometric technique for ^{130}Te



Heat sink
T ≅ 10 mK

Energy absorber
TeO_2 crystal
C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK

Thermal coupling
G ≅ 4 nW / K = 4 pW / mK

Thermometer
NTD Ge-thermistor
R ≅ 100 MΩ
dR/dT ≅ 100 kΩ/μK

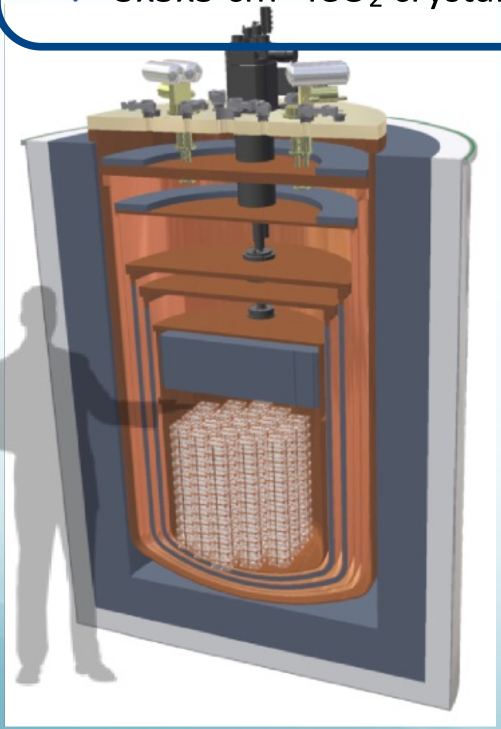
- Temperature signal: $\Delta T = E/C \cong 0.1$ mK for E = 1 MeV
- Bias: I ≅ 0.1 nA ⇒ Joule power ≅ 1 pW ⇒Temperature rise ≅ 0.25 mK
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T$ ⇒ $\Delta V = 1$ mV for E = 1 MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s
- Noise over signal bandwidth (a few Hz): $V_{rms} = 0.2$ μV

Energy resolution (FWHM): ≅ keV scale

CUORE: Cryogenic Underground Observatory for Rare Events

Searching for neutrinoless double beta decay of ^{130}Te

- ^{130}Te good DBD candidate: high natural abundance (34.2 %), reasonably high Q-value (2528 keV)
- TeO_2 is a compound with good mechanical and thermal properties containing ^{130}Te
- 5x5x5 cm^3 TeO_2 crystals have a high detection efficiency for $0\nu\beta\beta$ events: ~87.4%



CUORE setup

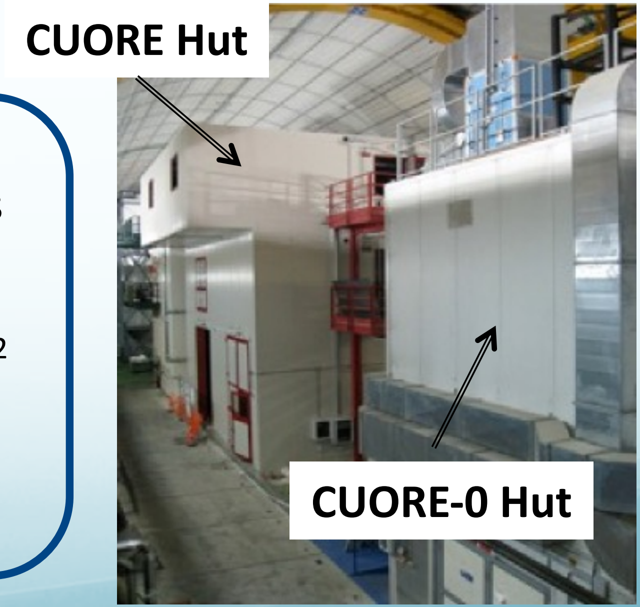
988 TeO_2 5x5x5 cm^3 crystals (750 g each)

Detector Mass: 741 kg TeO_2

^{130}Te mass (natural i.a.) : 206 kg of ^{130}Te

Array: 19 towers

In Hall A of LNGS



CUORE background goal: 0.01 counts/kg keV y

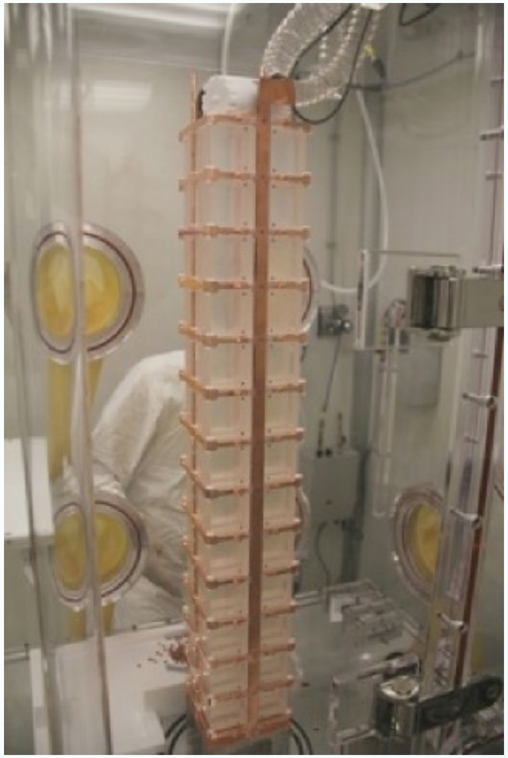
CUORE first phase: CUORE-0

1 CUORE-like tower of 13 planes - 4 crystals each

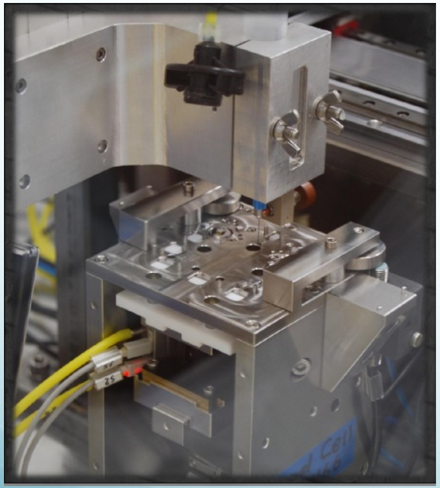
52 TeO_2 5x5x5 cm^3 crystals

Detector Mass: 39 kg TeO_2

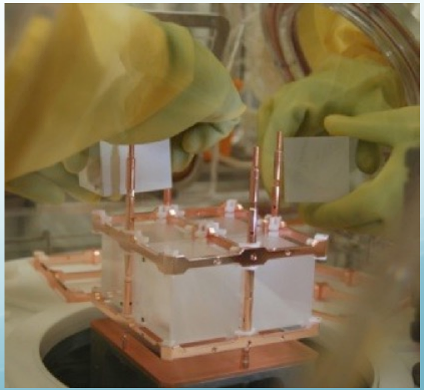
^{130}Te mass (natural i.a.): 11 kg of ^{130}Te



CUORE-0 assembly performed in **N_2 atmosphere** inside the new CUORE clean room following all the stages and using **all the equipment developed for CUORE**



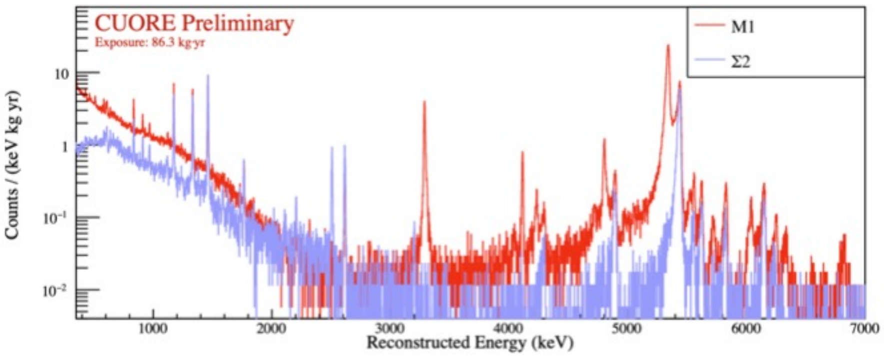
Gluing of thermistor to crystals was performed with the **new CUORE gluing semi-automatic machine**

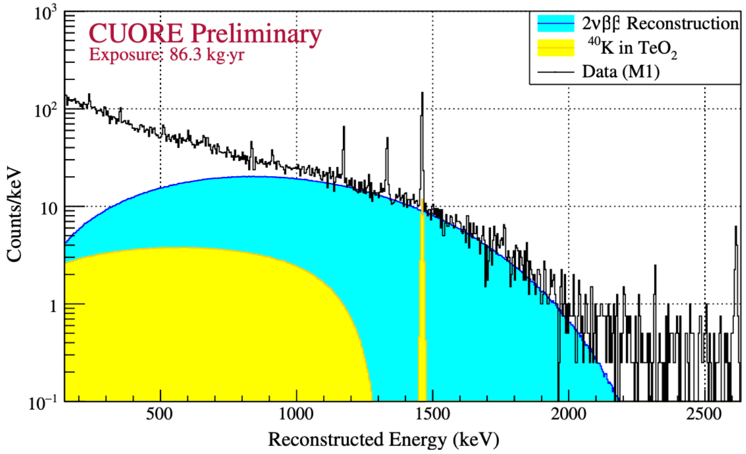


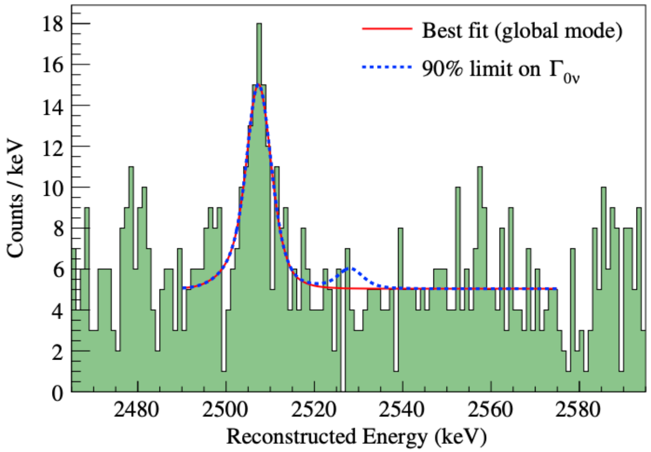
The assembly of the tower was done with the **CTAL (CUORE Tower Assembly Line)** providing radioactivity control and reproducible protocols

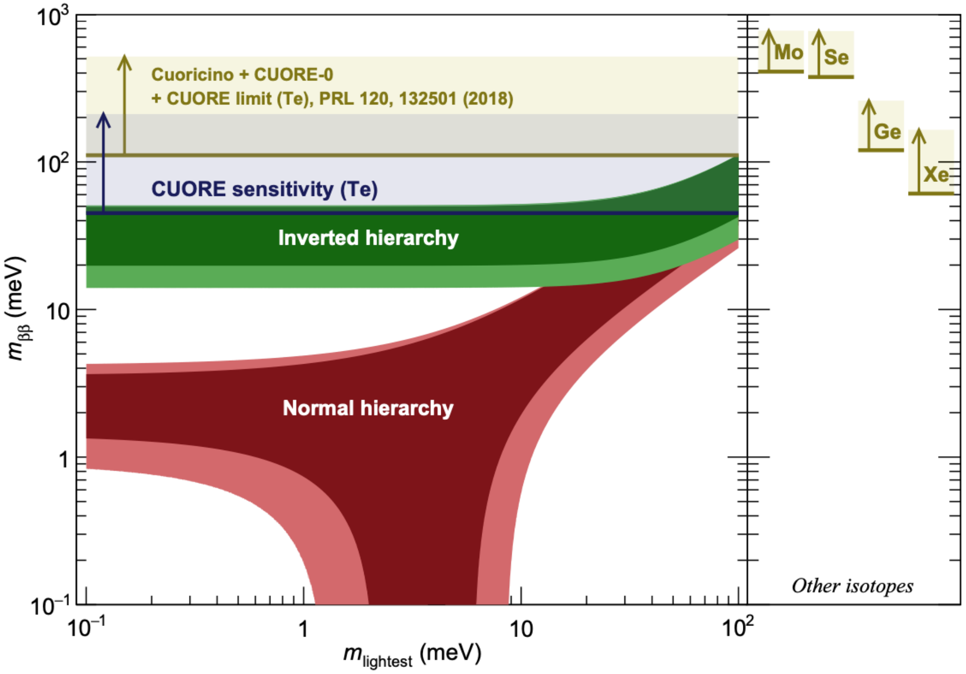
CUORE results 2020

- $^{130}\mathrm{Te}\ 2\beta$
- M1: multiplicity 1; $\Sigma 2$: M1+M2
- $T_{1/2}^{2\nu} = (7.9 \pm 0.1(stat) \pm 0.2(syst))\times 10^{20}$yr
- $T_{1/2}^{0\nu} > 3.2\times 10^{25}$yr (90% CL)



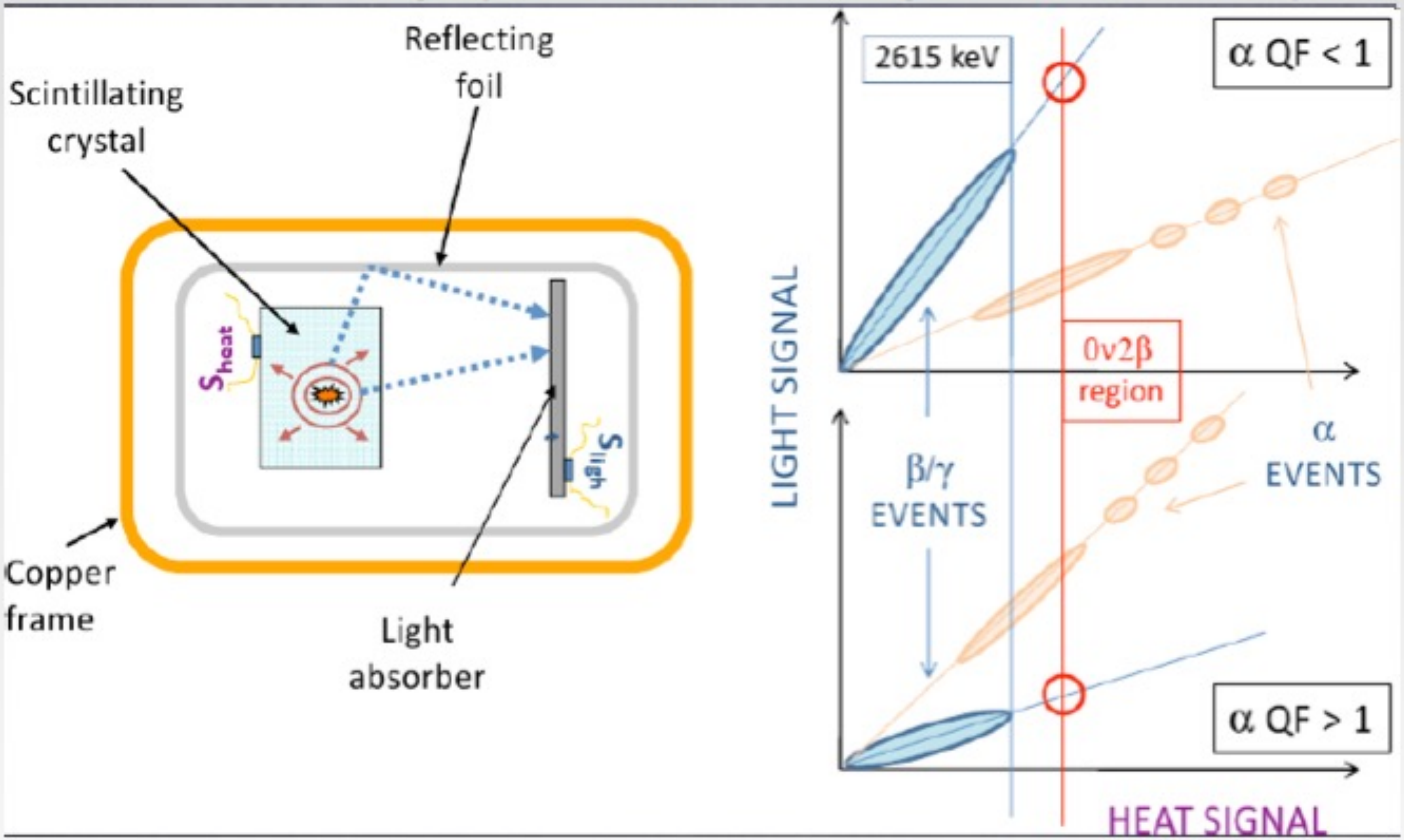






LUCIFER

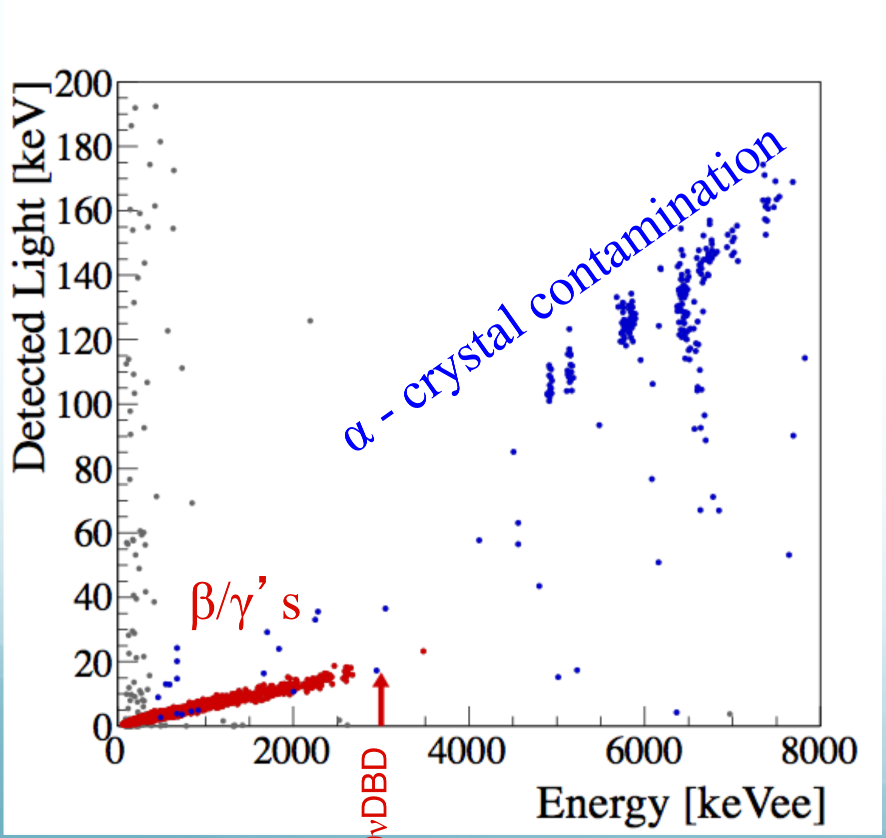
"CUORE" with scintillating crystal to suppress backgrounds < 0.001 cnt/(keV kg y)

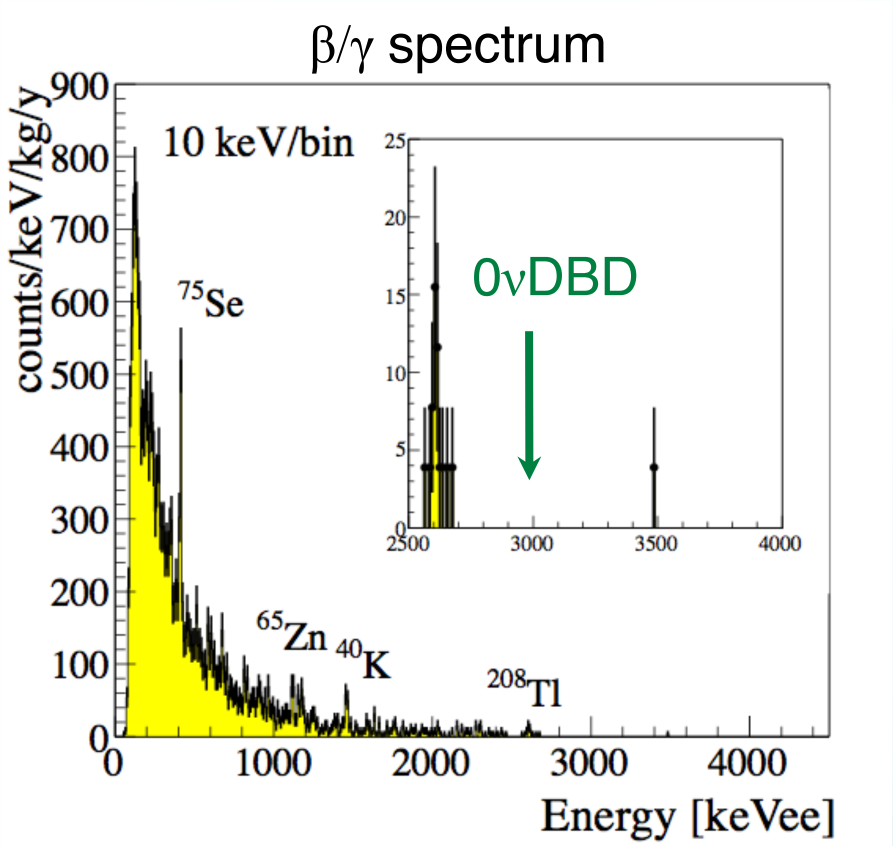


best candidate ZnSe, plan to use Cuoricino cryostat

LUCIFER: some results

- 431g Zn^{nat}Se crystal operated for 22 days.
  - ΔE@2615 keV = 13 keV FWHM
  - α background entirely identified via light pulse shape.

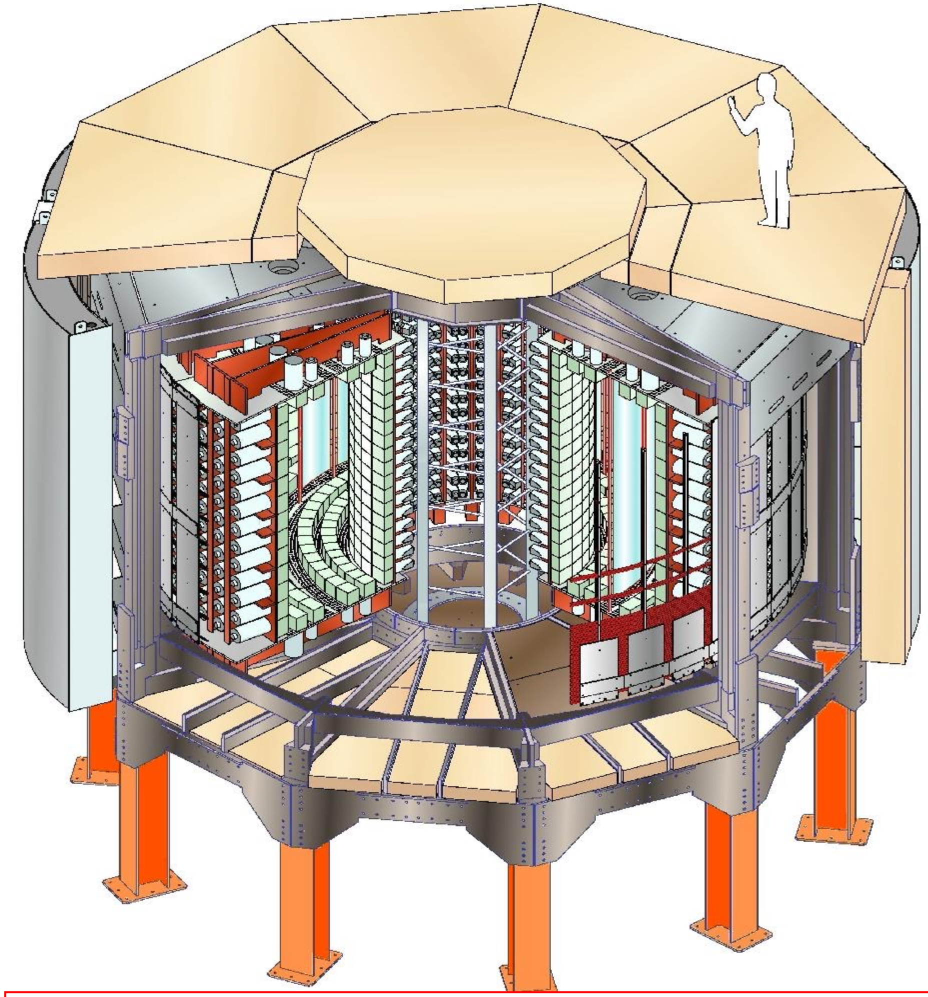




- One β/γ event above 2615 keV, in coincidence with several hits in nearby detectors (μ-spallation).
- Easily to tag via coincidence analysis in an array, or via a μ-veto.

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: **10 kg of ββ isotopes**

cylindrical, S = 20 m², 60 mg/cm²

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

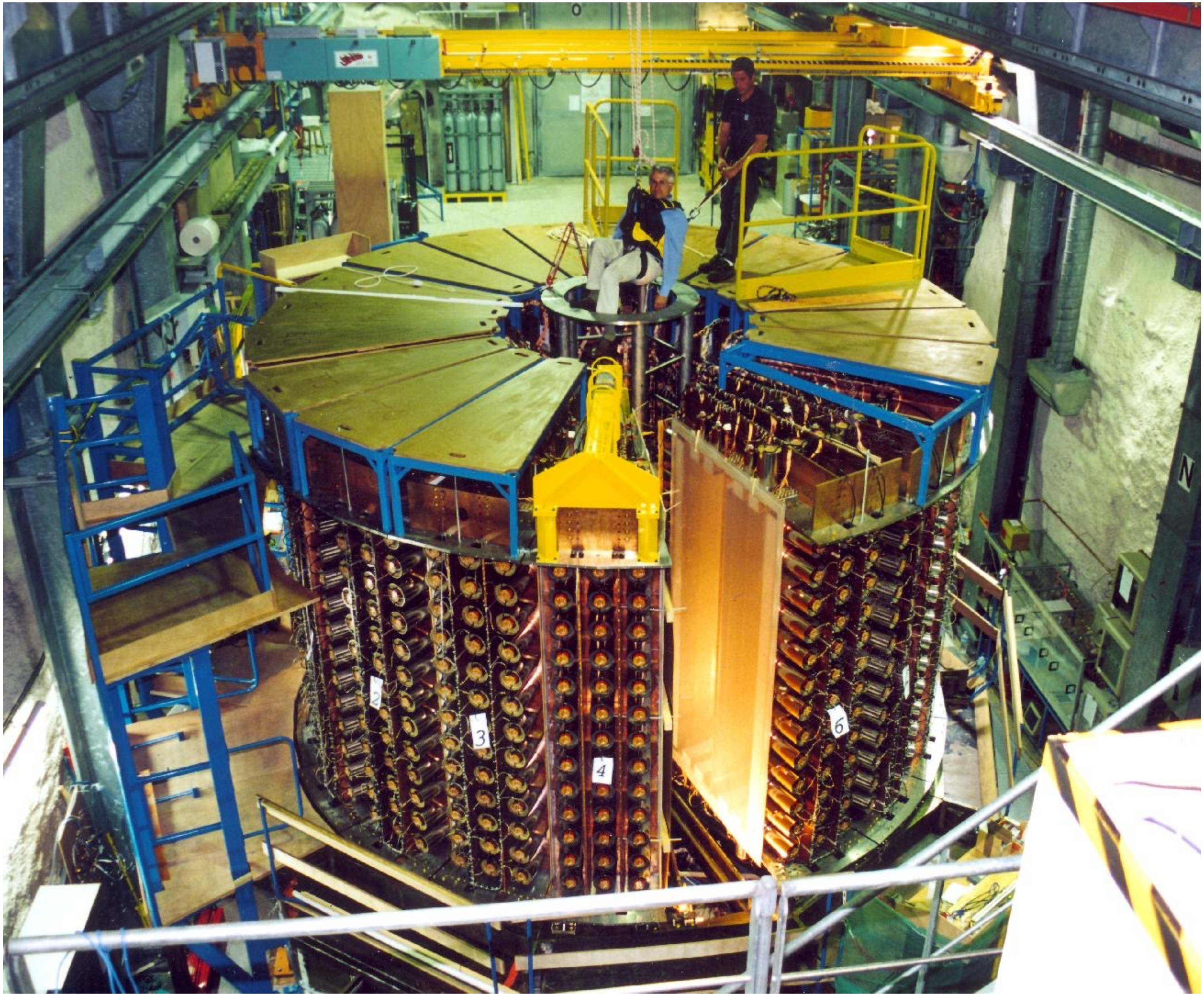
Magnetic field: **25 Gauss**

Gamma shield: **Pure Iron (18 cm)**

Neutron shield: **borated water + Wood**

Background: natural radioactivity, mainly ^{214}Bi et ^{208}Tl (γ 2.6 MeV)
Radon, neutrons (n,γ), muons, ββ(2ν)

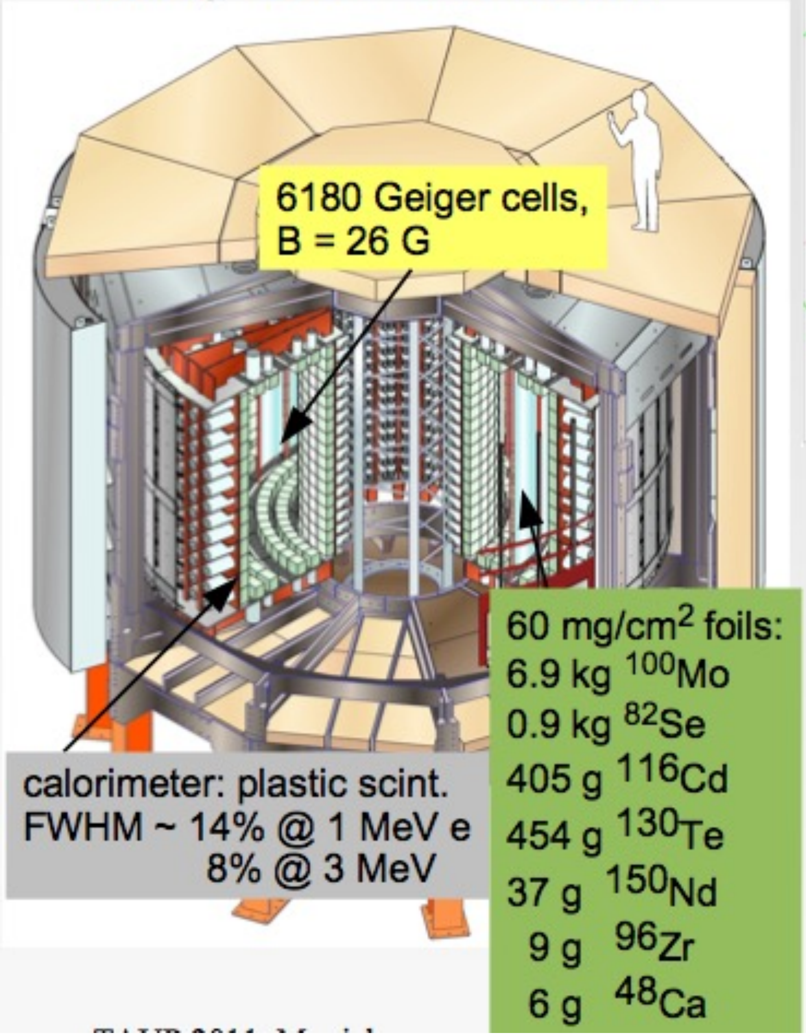
→ **Able to identify e^-, e^+, γ and α**



During installation AUGUST 2001

NEMO-3

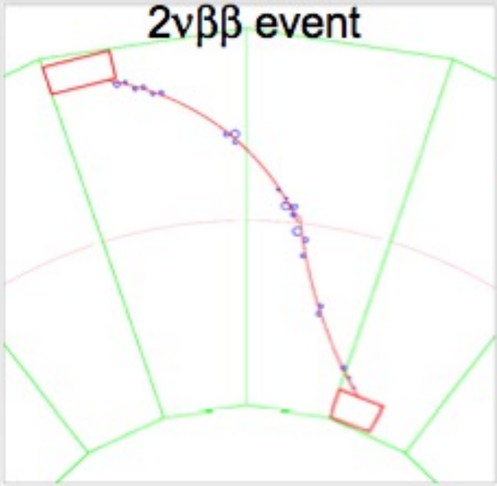
tracking – calorimeter detector



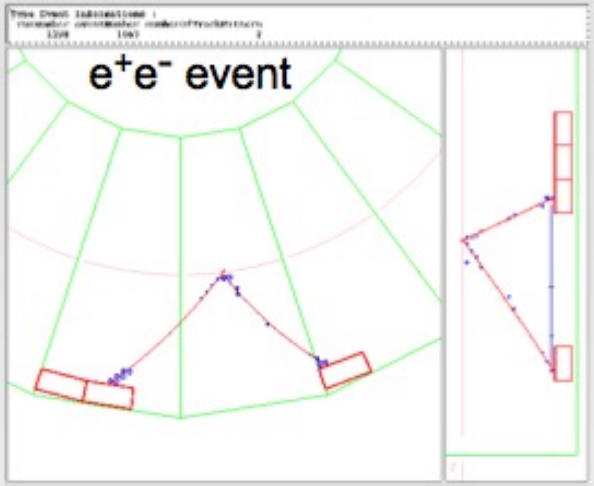
6180 Geiger cells,
B = 26 G

calorimeter: plastic scint.
FWHM ~ 14% @ 1 MeV e
8% @ 3 MeV

60 mg/cm^2 foils:
6.9 kg ^{100}Mo
0.9 kg ^{82}Se
405 g ^{116}Cd
454 g ^{130}Te
37 g ^{150}Nd
9 g ^{96}Zr
6 g ^{48}Ca



$2\nu\beta\beta$ event

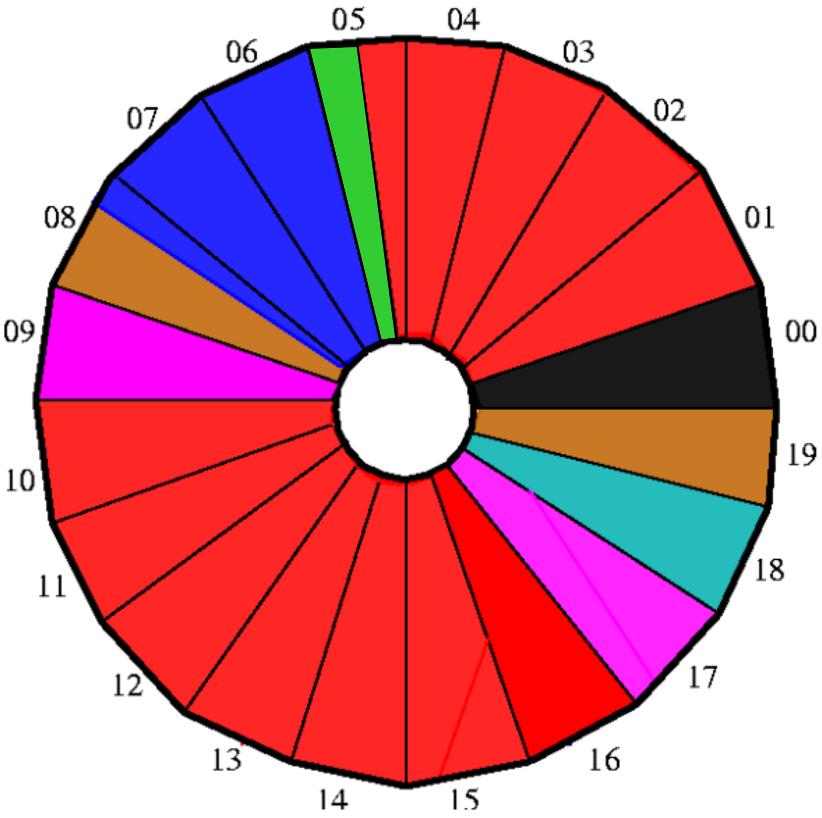


e^+e^- event

full event topology to identify backgrounds
different target materials can be used,
many results on $2\nu\beta\beta$ decays
BUT: poor energy resolution & low efficiency

data taking stopped Jan 2011

ββ decay isotopes in NEMO-3 detector



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

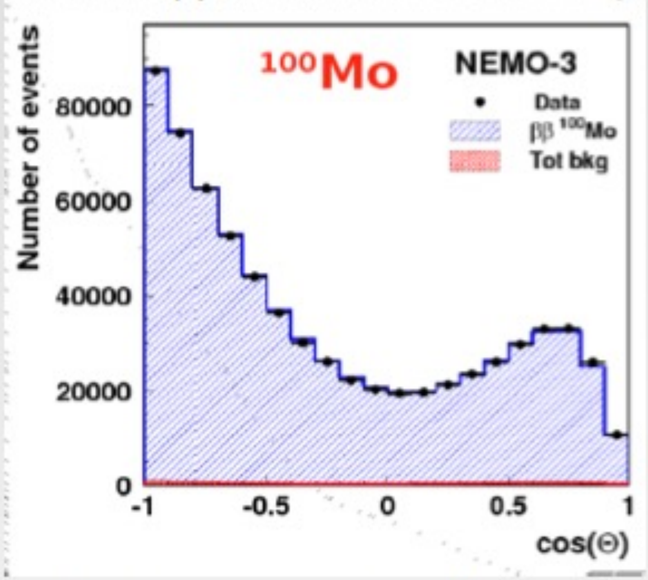
Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

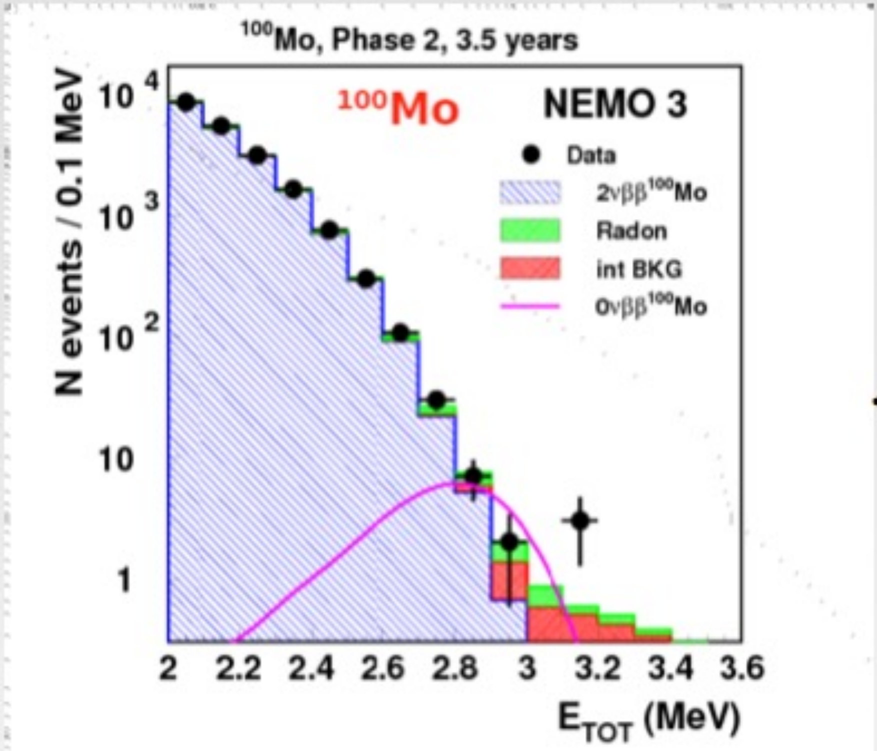
NEMO-3 results

700k 2νββ events "without" bkg



$T^{2\nu}_{1/2}=(7.16\pm0.54)\cdot10^{18}\,\mathrm{y}$ (prelim.)

2νββ results also for other six isotopes, see Victor Tretyak's talk at MEDEX 2011



[2.8 , 3.2] MeV:

ε(0ν) = 0.055

Tot MC= 11.0±0.8 , Data: 12 events

MC 2vbb = 5.8±0.4

MC radon = 2.5±0.4

MC int bkg=2.7±0.4 (^{214}Bi=0.4,^{208}Tl=2.3)

for 4.5 years

$T^{0\nu}_{1/2}>1.0\cdot10^{24}\,\mathrm{y}$

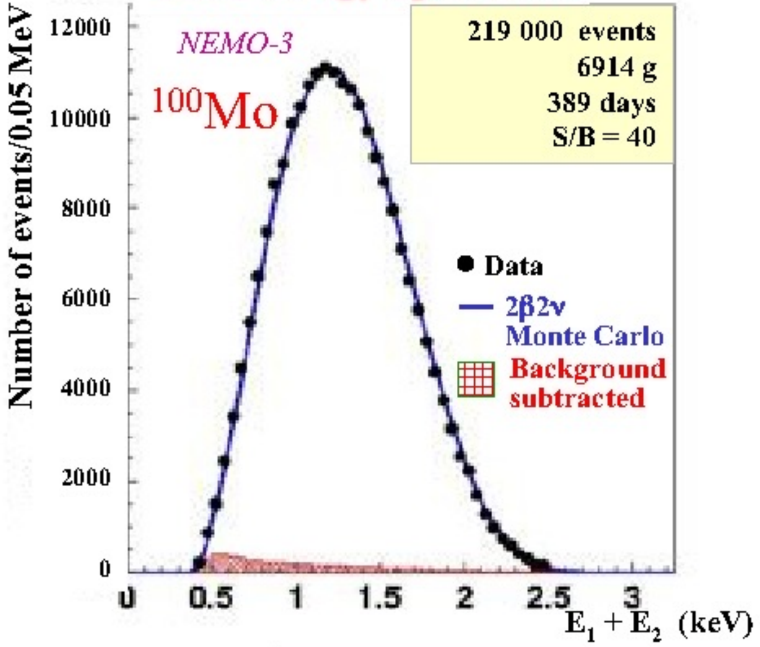
at 90% CL

$\langle m_{ee}\rangle$ < 0.5-1 eV

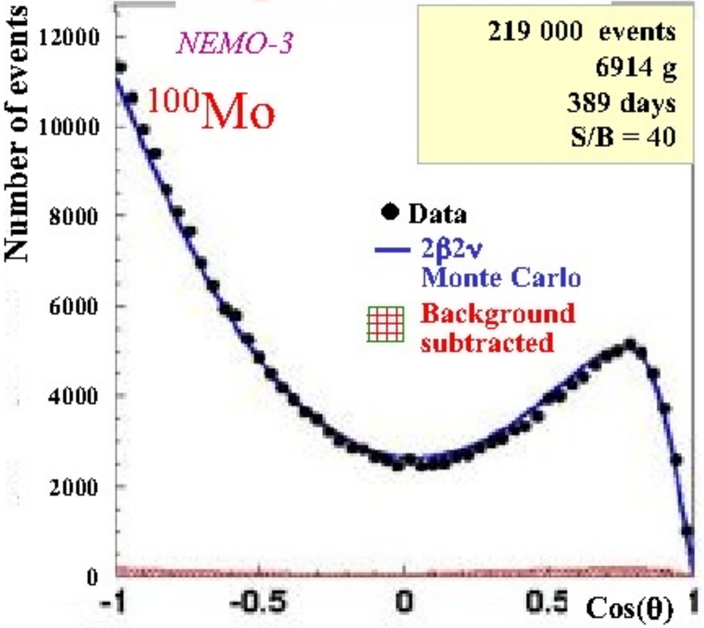
^{100}Mo ββ(2ν) Results

Phase 1 Feb. 2003 – Dec. 2004 WITH RADON

Sum energy spectrum



Angular distribution

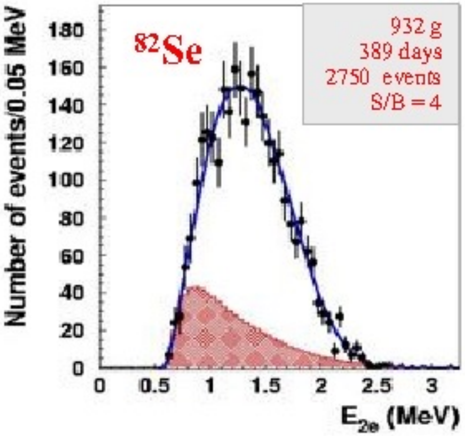


$T_{1/2}(\beta\beta 2\nu) = 7.11 \pm 0.02\ (\mathrm{stat}) \pm 0.54\ (\mathrm{syst}) \times 10^{18}$ **years**

Phys. Rev. Lett. 95 182302 (2005)

«ββ factory» → tool for precision test

Other Nuclei ββ(2ν) Results



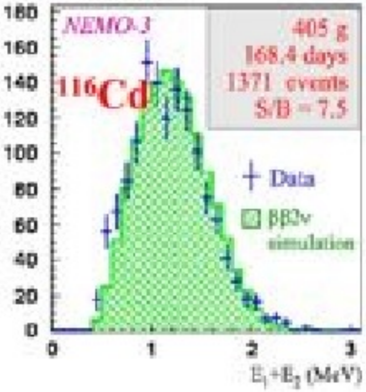
^{82}Se $T_{1/2} = 10.3 \pm 0.2\ (\text{stat}) \pm 1.0\ (\text{syst}) \times 10^{19}$ y

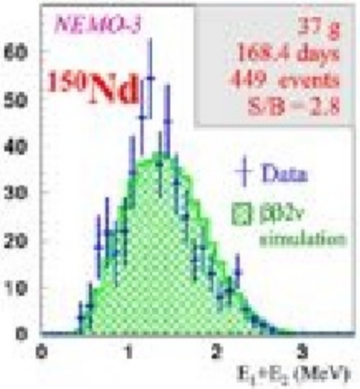
^{116}Cd $T_{1/2} = 2.8 \pm 0.1\ (\text{stat}) \pm 0.3\ (\text{syst}) \times 10^{19}$ y

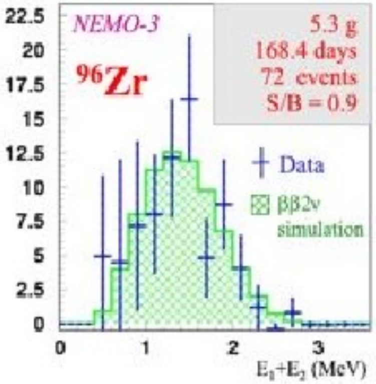
^{150}Nd $T_{1/2} = 9.7 \pm 0.7\ (\text{stat}) \pm 1.0\ (\text{syst}) \times 10^{18}$ y

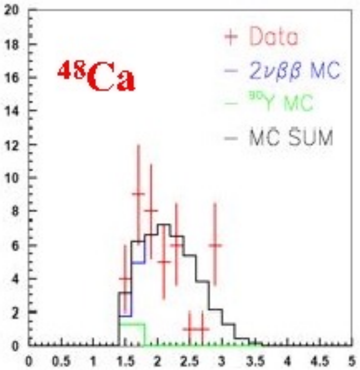
^{96}Zr $T_{1/2} = 2.0 \pm 0.3\ (\text{stat}) \pm 0.2\ (\text{syst}) \times 10^{19}$ y

^{48}Ca $T_{1/2} = 3.9 \pm 0.7\ (\text{stat}) \pm 0.6\ (\text{syst}) \times 10^{19}$ y







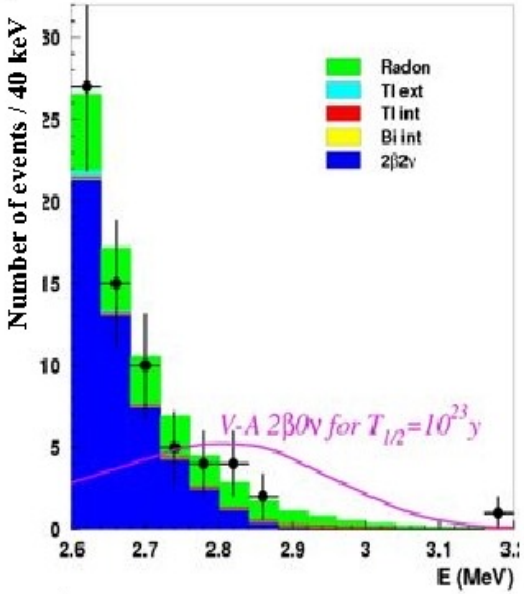


Background subtracted

$\beta\beta0\nu$ results with ^{100}Mo

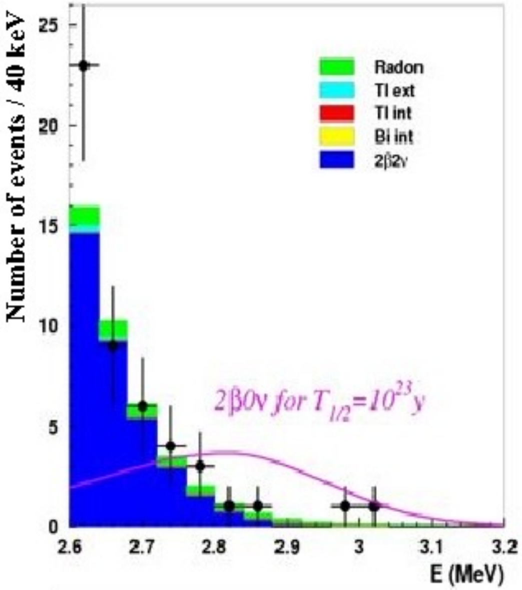
^{100}Mo, 7 kg

Phase I, High radon
394 days



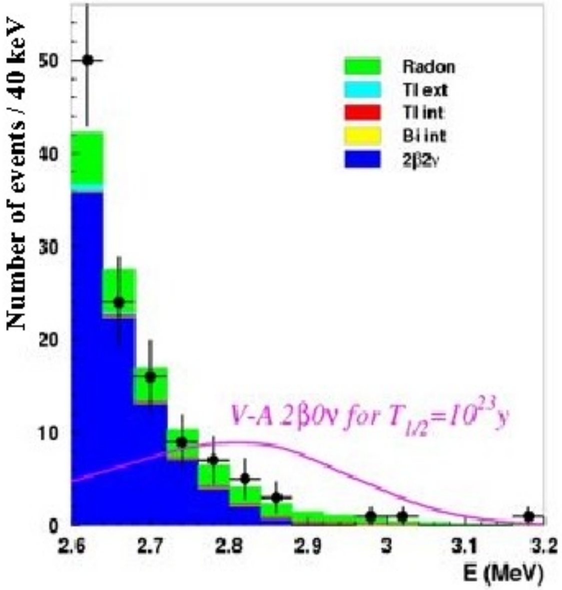
[2.8-3.2] MeV: $\varepsilon(\beta\beta0\nu) = 8$ %
Expected bkg = 8.1 events
$N_{observed} = 7$ events

Phase II, Low radon
299 days



[2.8-3.2] MeV: $\varepsilon(\beta\beta0\nu) = 8$ %
Expected bkg = 3.0 events
$N_{observed} = 4$ events

Phase I + II
693 days

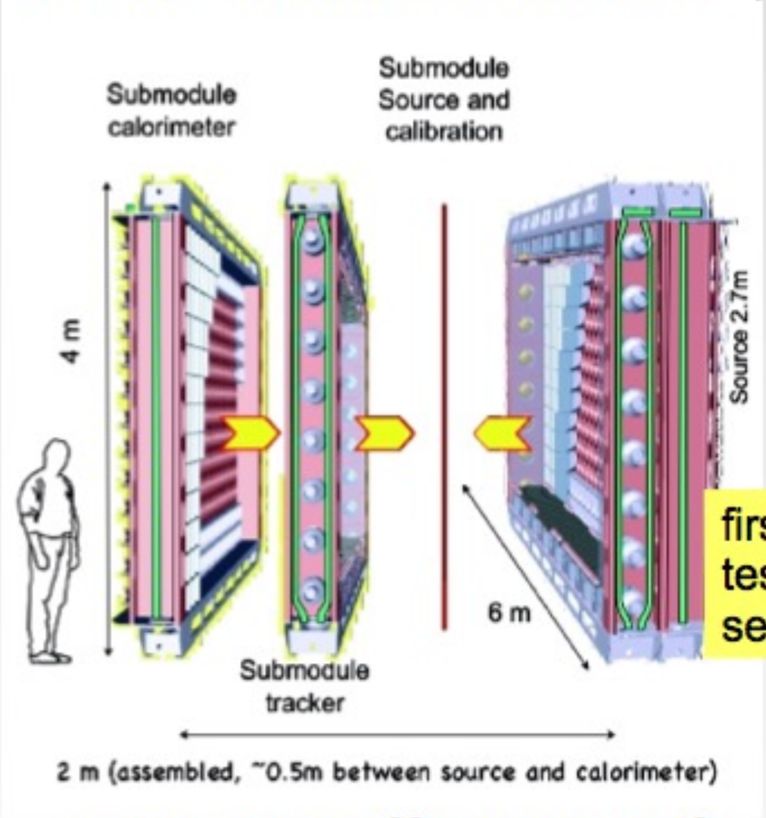


Phases I + II **$T_{1/2}(\beta\beta0\nu) > 5.8\ 10^{23}$ (90 % C.L.)**

$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{24}$ yr (90% C.L.)

SuperNEMO project

tracking + calorimeter, 20 modules

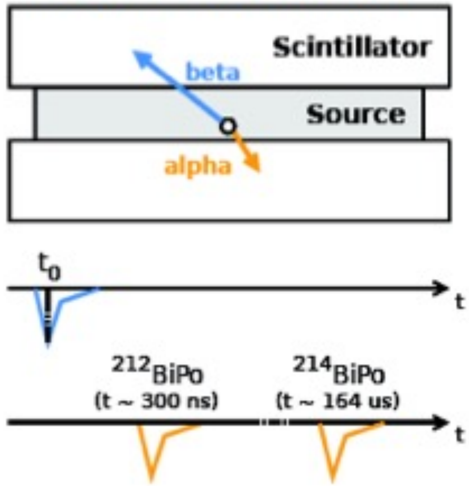


target material: ^{82}Se 40 mg/cm^2

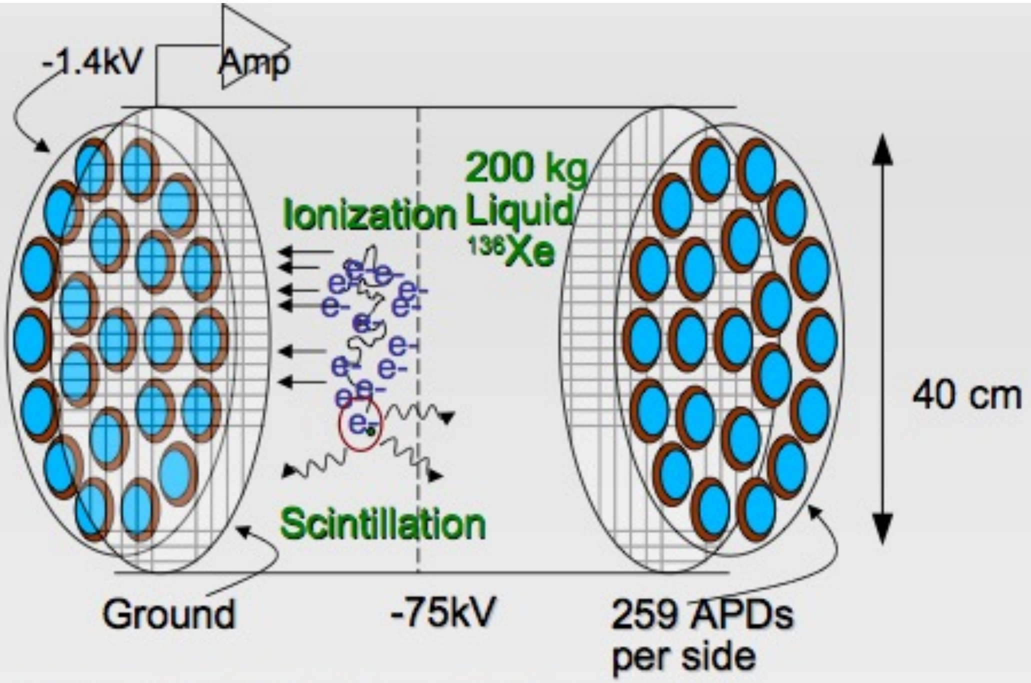
	NEMO3	SuperNEMO	
mass	8 kg	100-200 kg	
resolution	8%	4%	
efficiency	8%	30%	
foil bkg	<20	<2	µBq/kg (^{208}Tl)
	<300	<10	µBq/kg (^{214}Bi)
sensitivity	1.4x10^{24}	1x10^{26}	$T_{1/2}$ 90% CL

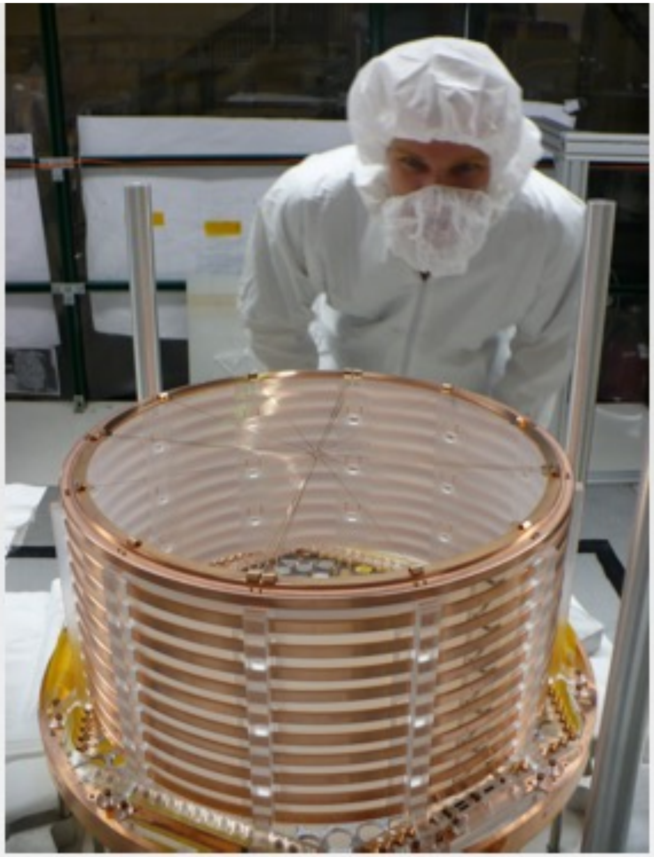
first module end 2013
tests background, ...
sensitivity ~ GERDA I

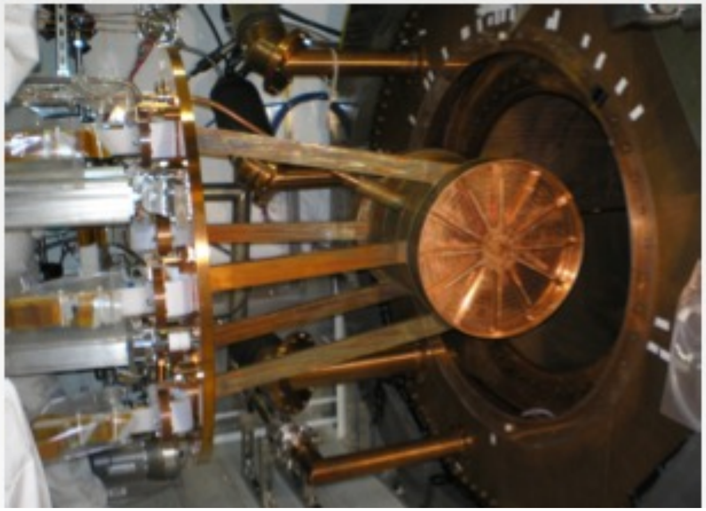
BiPo detector (3 m^2) in 2012
for foil measurement



EXO 200 (2β decay of ^{136}Xe)







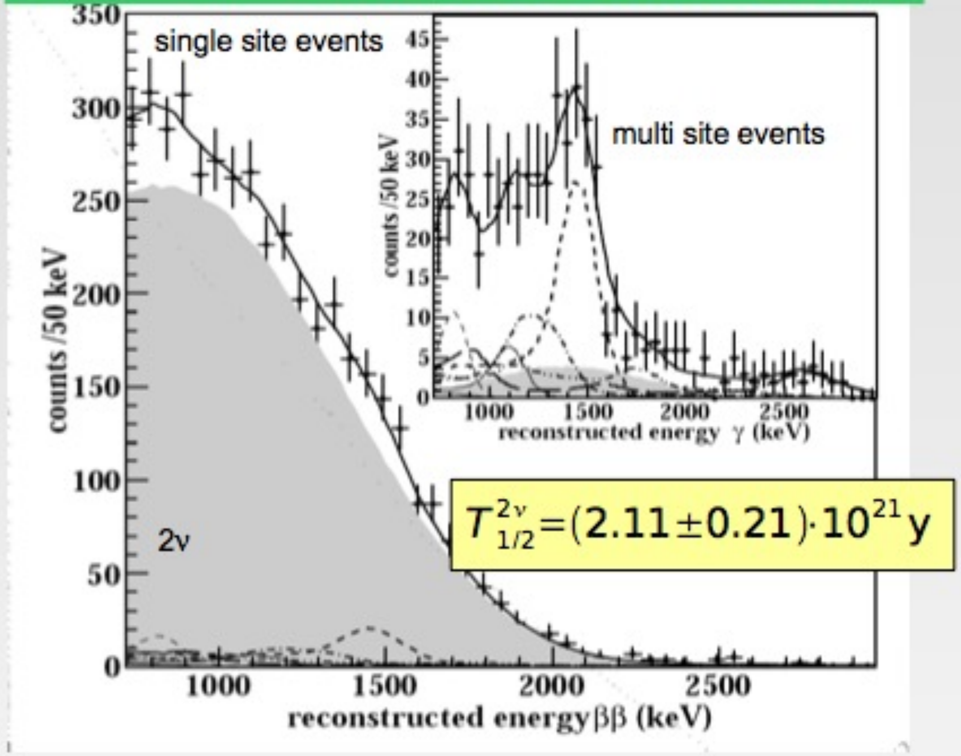
engineering run Dec 2010, 140 kg ^{136}Xe filled in spring,
cathode at -8 kV, σ = 4.5% at 2.6 MeV using ionization,

design: σ=1.6% using ionization+scintilation
0νββ $T_{1/2}$ sensitivity 6.4x10^{25} y (90% CL), testing Hd-Ms

EXO 200 first results

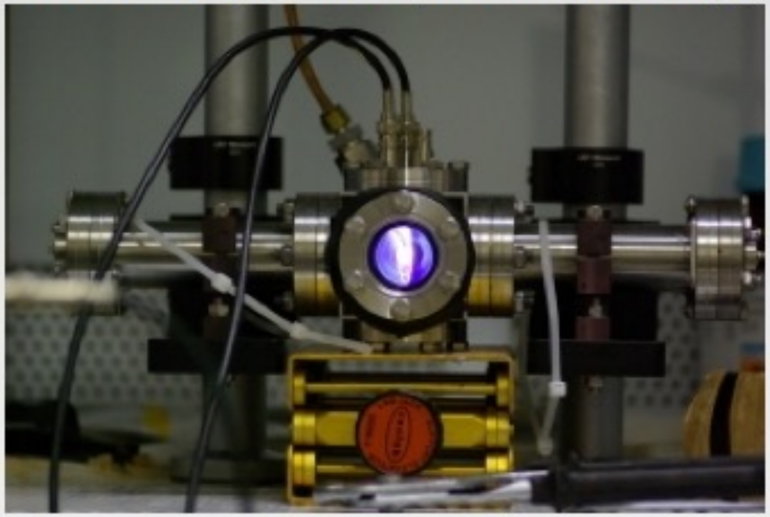
$^{136}Xe \rightarrow {}^{136}Ba + 2e^- + (2\nu_e)$;
$Q = 2479$ keV

first $T^{2\nu}$ for ^{136}Xe EXO200: arXiv:1108.4193



$T^{2\nu}_{1/2} = (2.11 \pm 0.21) \cdot 10^{21}$ y

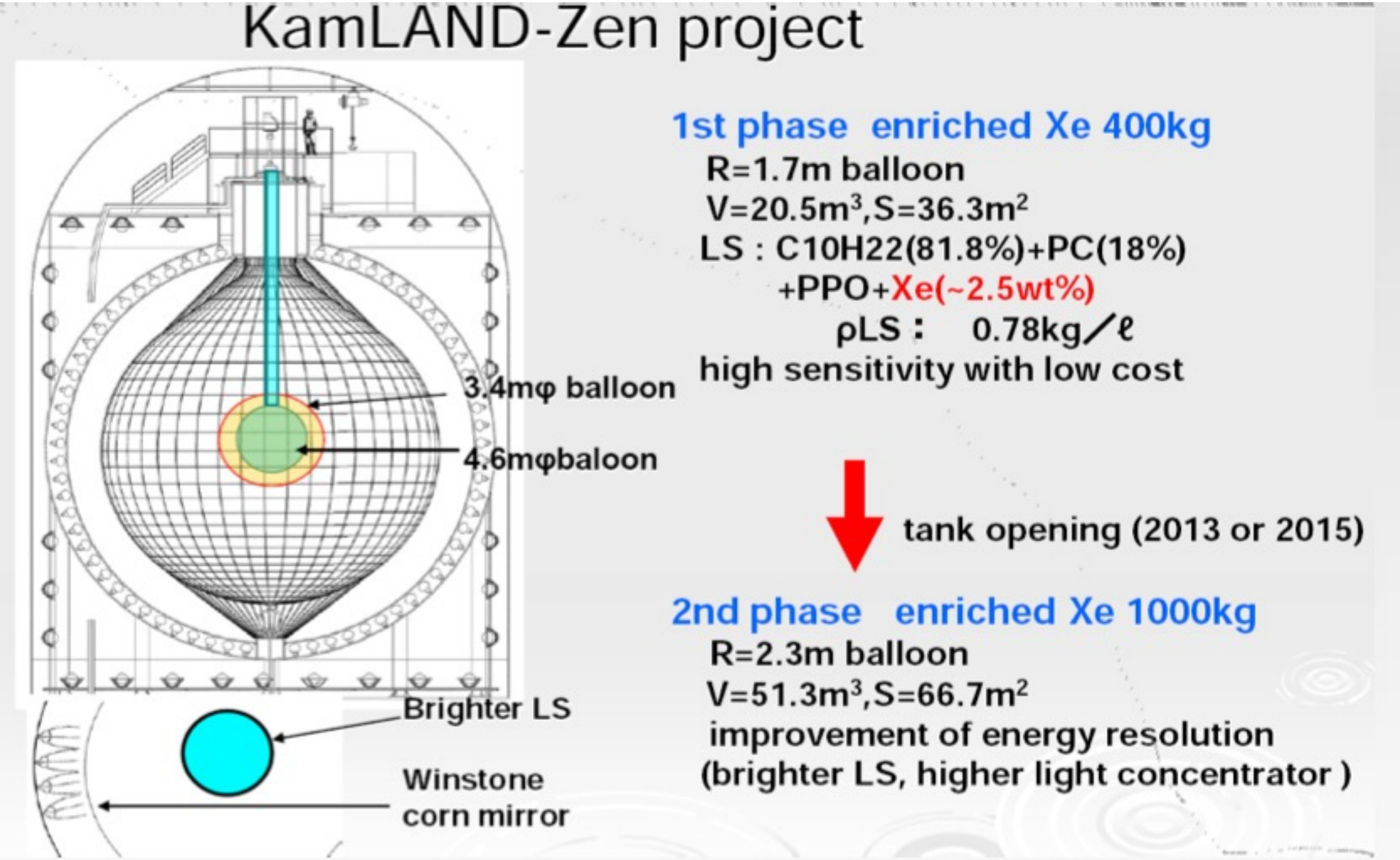
for future 1t experiment: plan to use Ba tagging



only 2νββ background would remain

also: R&D on gas TPC continuing

KAMLAND-Zen



KamLAND-Zen project

1st phase enriched Xe 400kg

R=1.7m balloon

$V=20.5m^3, S=36.3m^2$

LS : C10H22(81.8%)+PC(18%)
+PPO+Xe(~2.5wt%)

ρLS : 0.78kg／ℓ

high sensitivity with low cost

tank opening (2013 or 2015)

2nd phase enriched Xe 1000kg

R=2.3m balloon

$V=51.3m^3, S=66.7m^2$

improvement of energy resolution
(brighter LS, higher light concentrator)

3.4mφ balloon

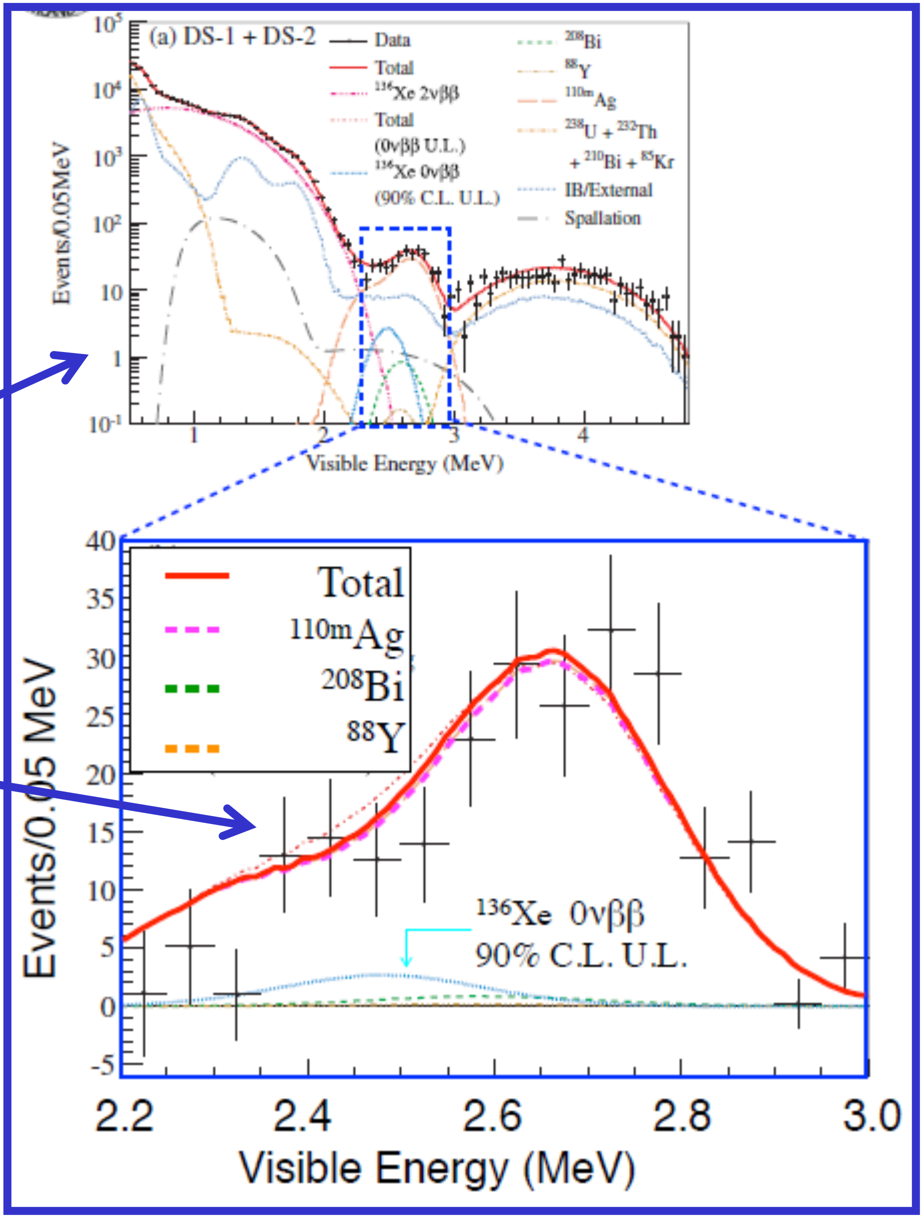
4.6mφbaloon

Brighter LS

Winstone corn mirror

KAMLAND-Zen

13 tons of liquid scintillator
loaded with 300 kg of ^{136}Xe
contained in a nylon balloon
immersed in 1 kton scintillator
of the KamLAND set-up



Full spectrum

Zoom in the region of DBD

KamLAND-Zen coll., Phys.Rev.Lett.110:062502,2013

SNO+

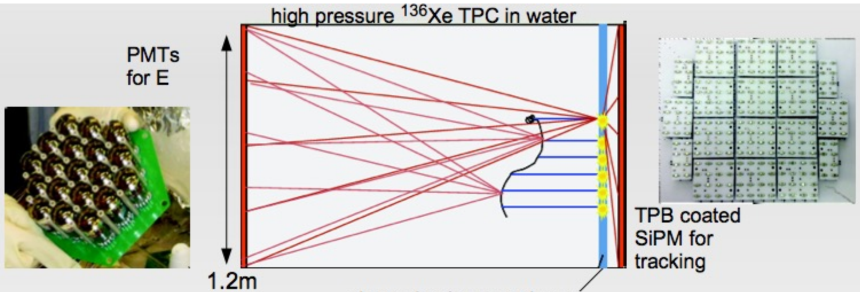
0.1% of ^{nat}Nd
--> 44 kg ^{150}Nd

6.8% FWHM
@ 3MeV

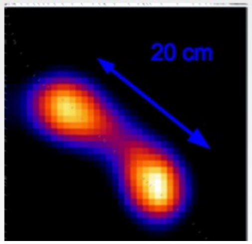
3y sensitivity
5.5x10^{24} y (90%CL)

start filling 2013,
Nd later

NEXT



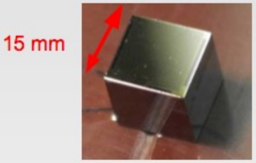
MC of 2νββ event: topological bkg supression



Conceptual Design Report: arXiv:1106.3630
- 100 kg ^{136}Xe already in hand
- extremely low bkg B ~ 0.0002 cnt/(keV kg y)
- extremely good FWHM 0.8% at 2.5 MeV
- "easy" to build
- "little" R&D needed, several proto-types exist can be ready in 2013

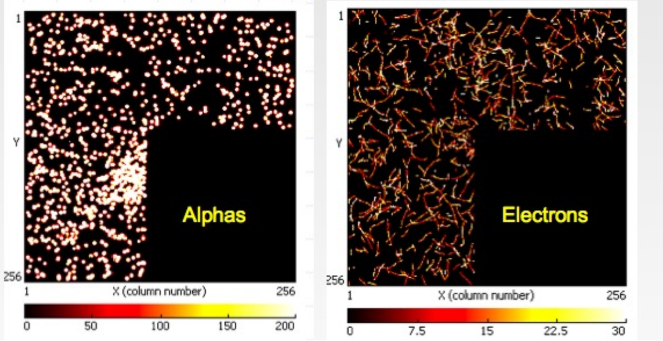
COBRA

Use large amount of CdZnTe Semiconductor Detectors with 55 μm pixel readout: as solid state TPC

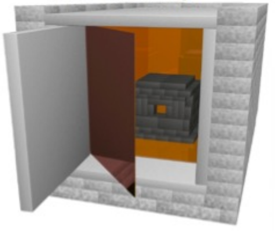


currently upgrade to 64 detector setup with new DAQ + shielding

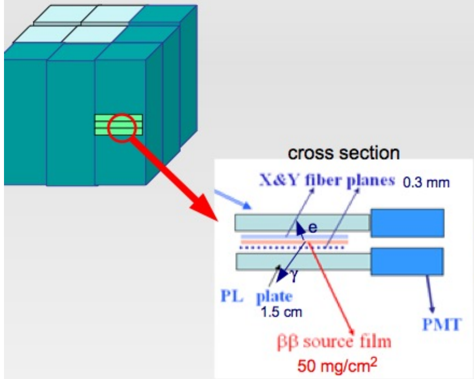
simulation of detector response



new shielding

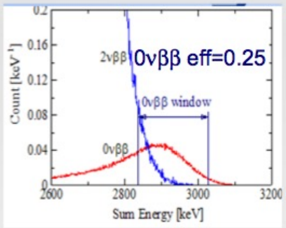


MOON



$E=E_{fiber}+E_{PL}$

σ=1.7-2.2%



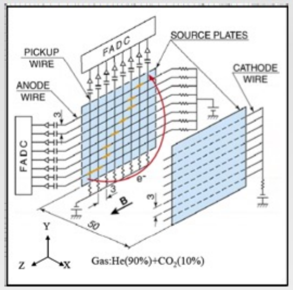
position,timing, E_{fiber}/E_{PL} for bkg rejection --> only 2νββ bkg

MOON-1 R&D: 6 layers pf PL + 5 Mo films (94.5% ^{100}Mo) of 40 mg/cm^2, 56 PMTs inside active+passive shield of ELEGANT V, σ = 2.9% at 3 MeV

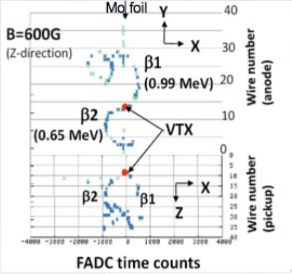
Phase I,II,III with 30, 120, 480 kg foreseen with 1.5, 4.1, 20 x 10^{25} y (90 % CL) sensitivity for ^{100}Mo or 3.2, 11.2, 59 x 10^{25} y (90% CL) sensitivity for ^{82}Se

DCBA

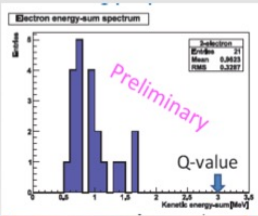
foil in drift chamber with uniform B



DCBA T2 9 cm x 26 cm x 26 cm
FWHM @ 3 MeV = 6.2%



21 2νββ candicates

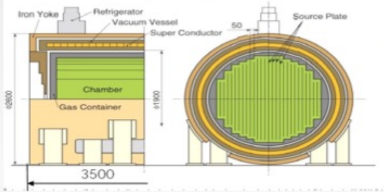


measured at KEK !!
powerful bkg rejection !!

T2 chamber in T3 magnet (>2 kG)

next step:
FWHM<5%?

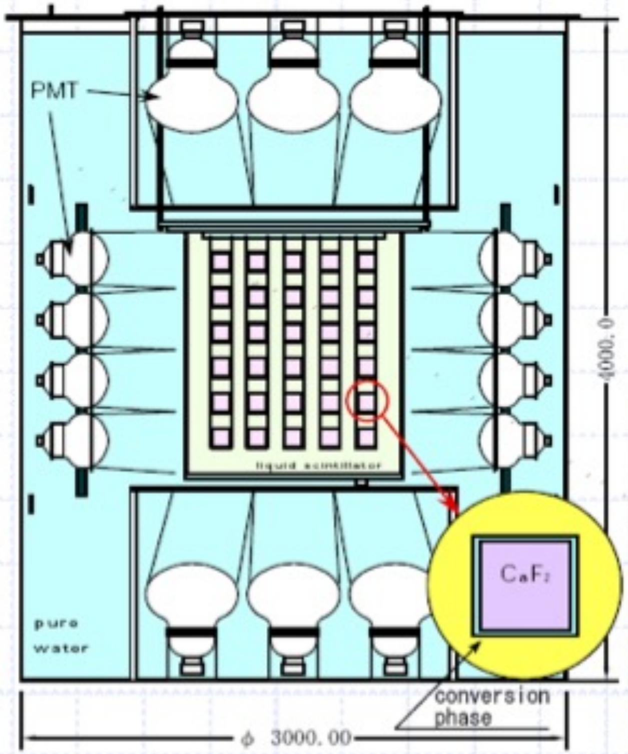
Magnetic Tracking Detector
(temporary name)

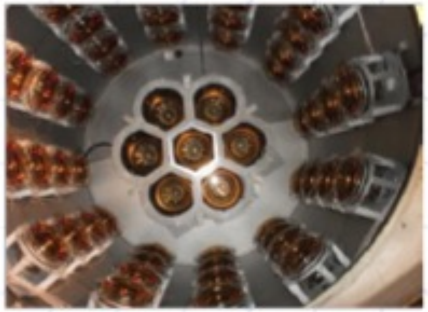


the future

CANDLES III(U.G.)

- CaF_2(pure)
  - 10^3 cm^3 × 96 crystals; 305 kg (^{48}Ca;350 g)
- Liquid scintillator
  - two phase system
  - Purification system
- H_2O Buffer
  - passive shield
- PMTs
  - 17" PMT (× 14) : R7250
  - 13" PMT (× 48) : R8055





- Run will start at autumn 2011

R&D enrichment of ^{48}Ca with Crown Ether chromatography

DAMA – Search for ββ decays

Many ββ decay modes of several isotopes have been investigated by DAMA and DAMA+INR-Kiev

❑ Active source technique

Scintillator	Isotopes
$CaF_2(Eu)$	Ca-40, Ca-46, Ca-48
CeF_3	Ce-136, Ce-138, Ce-142
BaF_2	Ba-130
$ZnWO_4$	Zn-64, Zn-70, W-180, W-186
$CeCl_3$	Ce-136, Ce-138, Ce-142
$CdWO_4$	Cd-108, Cd-114
$^{106}CdWO_4$	Cd-106
$^{116}CdWO_4$	Cd-116
Liq. Xe	Xe-134, Xe-136

Many 2ε, $\varepsilon\beta^+$ and $2\beta^+$ decays investigated

- → observation (complementary to $2\beta^-$) of 0ν mode could help to distinguish among the mechanisms of 0ν2β decay (non-zero neutrino mass or right-handed admixtures in weak interactions)
- → Possibility to study resonant enhanced 2ε decay

❑ Passive source technique

Sample	Isotopes
Ru	Ru-96; Ru-104
Os	Os-184; Os-192
Pt	Pt-190, Pt-198
Dy_2O_3	Dy-156, Dy-158
$^{100}MoO_3$	Mo-100
Cd	Cd-106

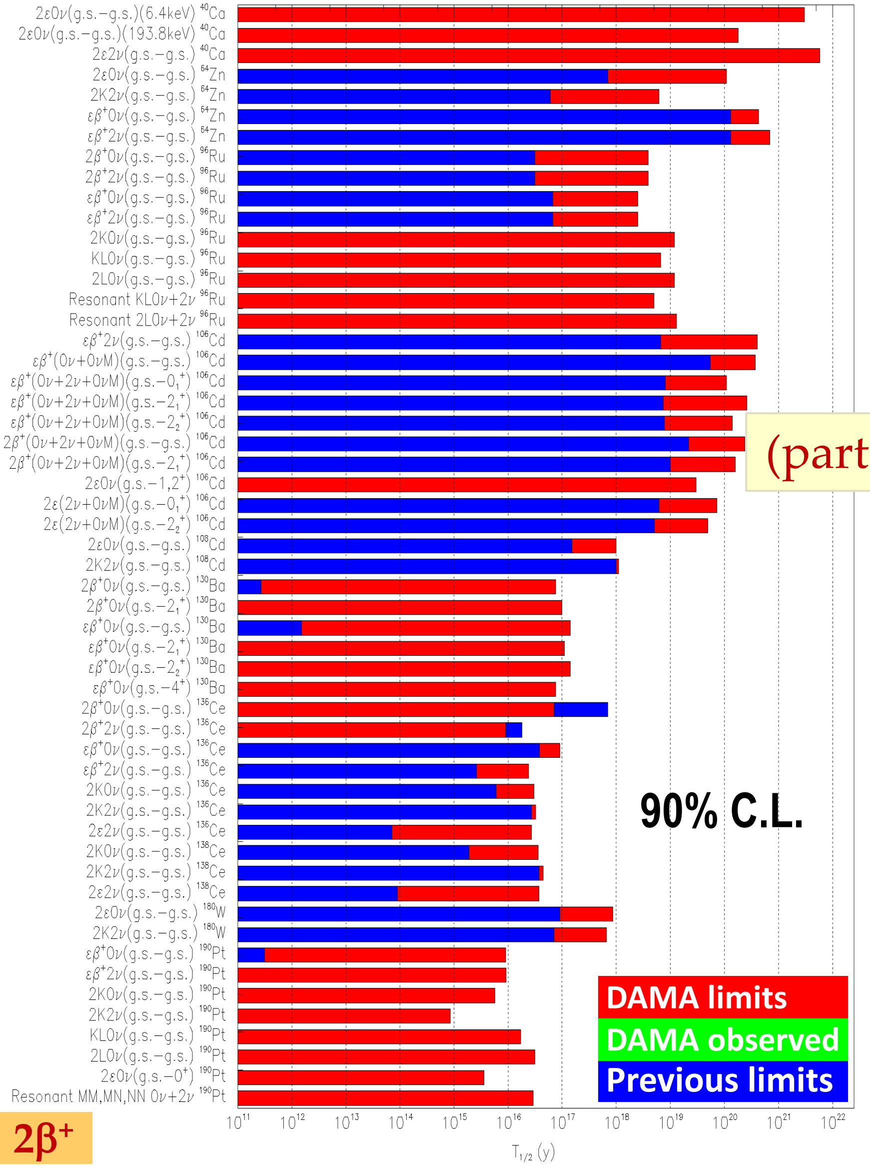
Search for ββ decay modes in various isotopes at DAMA and STELLA set-ups

DAMA and DAMA/Kiev

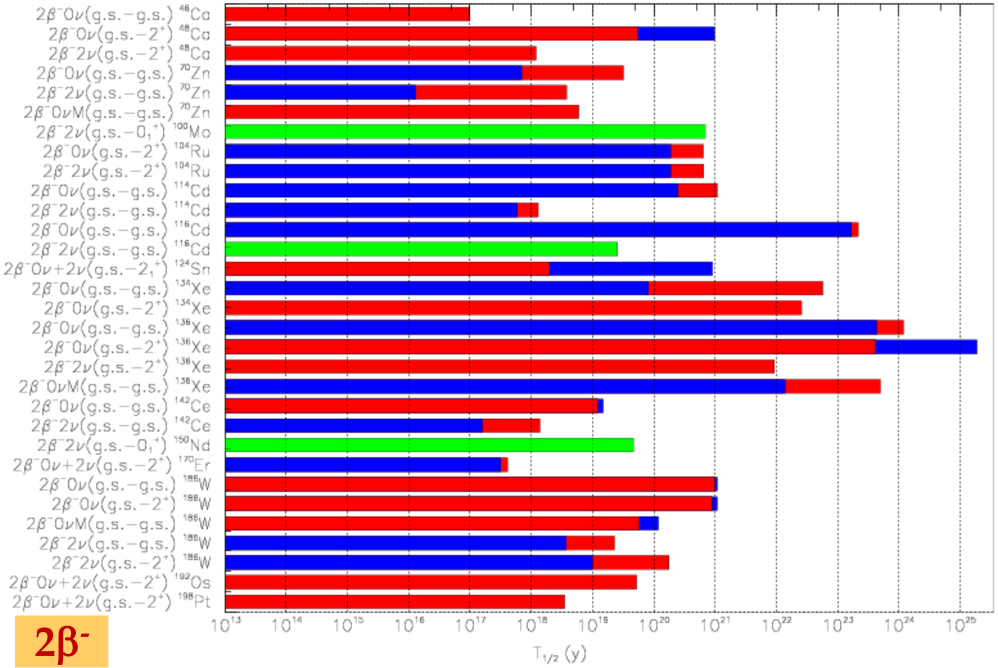
New observations:

ARMONIA:	$2\nu2\beta^-$ decay	$^{100}Mo \rightarrow ^{100}Ru(0_1^+)$	NPA846(2010)143
AURORA:	$2\nu2\beta^-$ decay	$^{116}Cd \rightarrow ^{116}Sn$	PRD98(2018)092007
Nd_2O_3-HPGe:	$2\nu2\beta^-$ decay	$^{150}Nd \rightarrow ^{150}Sm(0_1^+)$	NPAE19(2018)95

(partial list)



$2\beta^+$



$2\beta^-$

- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes (^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, ^{184}Os, ^{156}Dy, ^{158}Dy, …).
- First searches for resonant $0\nu2\varepsilon$ decays in some isotopes

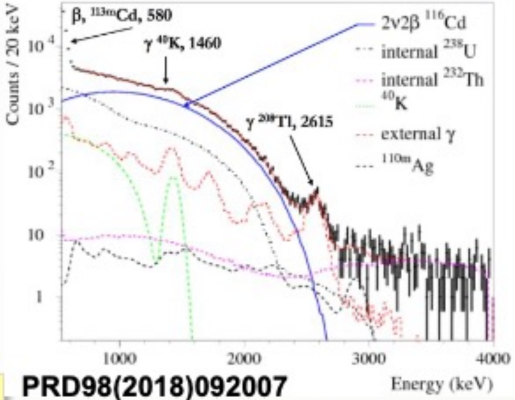
DAMA results in the search for double β decay

Profiting of the low background features of its set-ups, DAMA has achieved competitive results in the investigation of many rare processes and double beta decays

First or improved results for 2β decays of ~30 candidate isotopes: ^{40,46,48}Ca, ^{64,70}Zn, ^{100}Mo, ^{96,104}Ru, ^{106,108,114,116}Cd, ^{112,124}Sn, ^{134,136}Xe, ^{130}Ba, ^{136,138,142}Ce, ^{156,158}Dy, ^{180,186}W, ^{184,192}Os, ^{190,198}Pt

The best experimental sensitivities in the field for 2β plus decays:

- ⇒ $0\nu\varepsilon\beta^+$ or $0\nu2\beta^+$ may help to refine the mechanism of the $0\nu2\beta^-$ decay (Majorana ν mass vs right-handed admixtures in the weak interaction)
- ⇒ Possible resonant enhancement of the capture rate for $0\nu2\varepsilon$, due to a mass degeneracy between the initial and final nucleus



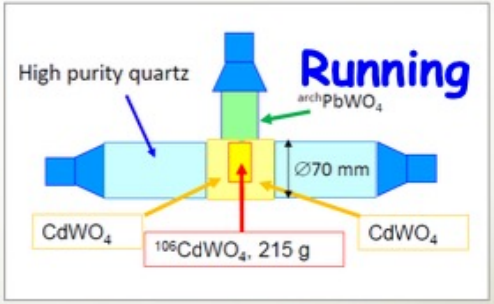
PRD98(2018)092007

Recent DAMA results

AURORA experiment

Two ^{116}CdWO$_4$ crystal scintillators enriched at 82%, mass=1.16 kg, T~4yr

- ✓ $T_{1/2}(2\nu2\beta) = 2.63^{+0.11}_{-0.12} \times 10^{19}$ yr (the most accurate value)
- ✓ $T_{1/2}(0\nu2\beta) \geq 2.2 \times 10^{23}$ yr (the strongest limit) ⇒ $\langle m_\nu \rangle < (1.0 - 1.7)$ eV



^{106}CdWO$_4$ crystal scintillator (^{106}Cd @ 66%) in coincidence with two CdWO$_4$

Sensitivity to $2\nu\varepsilon\beta^+$: $T_{1/2} > 3\times10^{21}$ yr (theoretical: $10^{20} - 10^{22}$ yr)

Highly purified Nd$_2$O$_3$ source (2.38 kg) in **GeMulti** (4 HPGe) set-up

Study of double coincidences from 2β2ν decay $^{150}\text{Nd} \rightarrow {}^{150}\text{Sm}(0_1^+$, 740.5 keV)

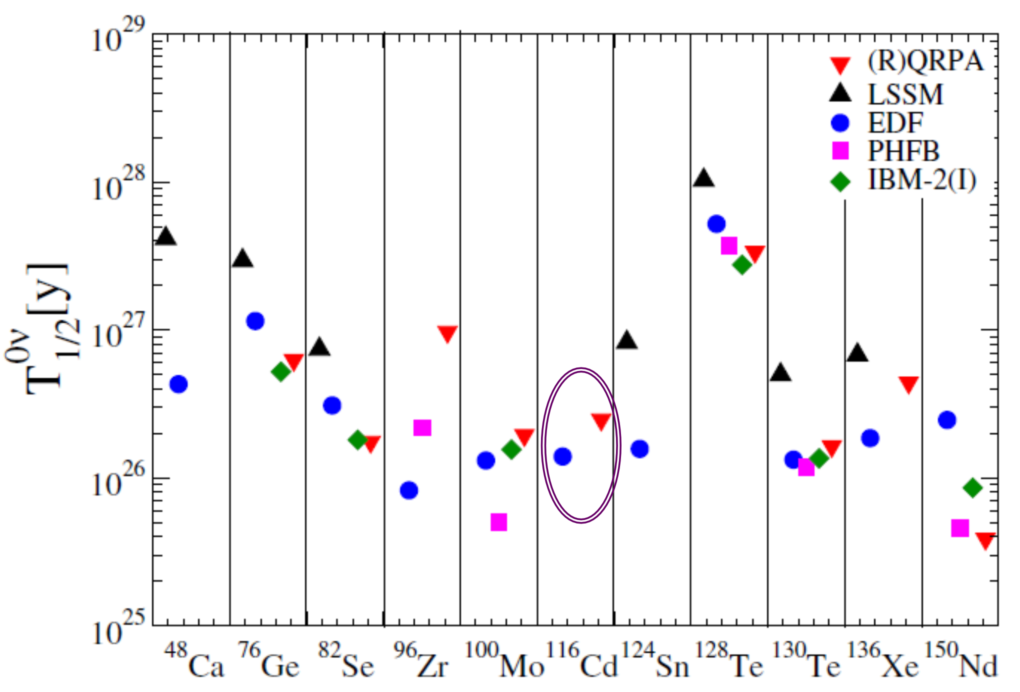
⇒ $T_{1/2} = [4.8^{+4.1}_{-1.9}(\text{stat}) \pm 0.5\,(\text{syst})] \times 10^{19}$ yr in agreement with previous results

Preliminary results in **Nucl.Phys.At.Energy 19(2018)95**

2β physics with enriched $^{116}CdWO_4$ crystal scintillators

^{116}Cd – one of the best candidates to search for 2β0ν decay:

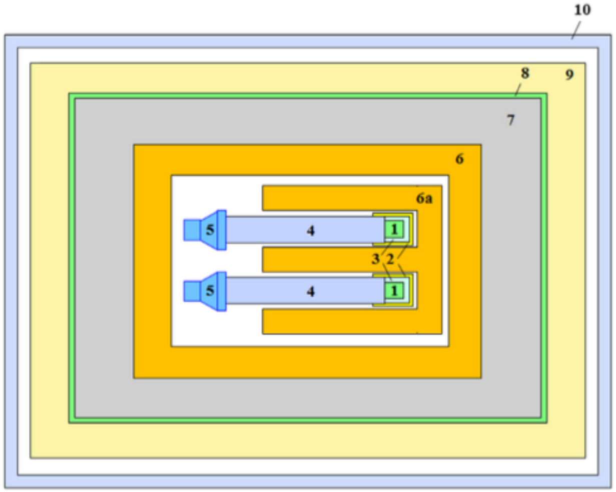
- $Q_{2\beta}$ = 2813.5(13) keV
- δ = 7.5%
- promising theoretical calculation
- isotopic enrichment in large amount by cheap centrifugation method



J.D. Vergados, H. Ejiri, F. Simkovic, RPP 75 (2012) 106301
– m_ν = 50 meV

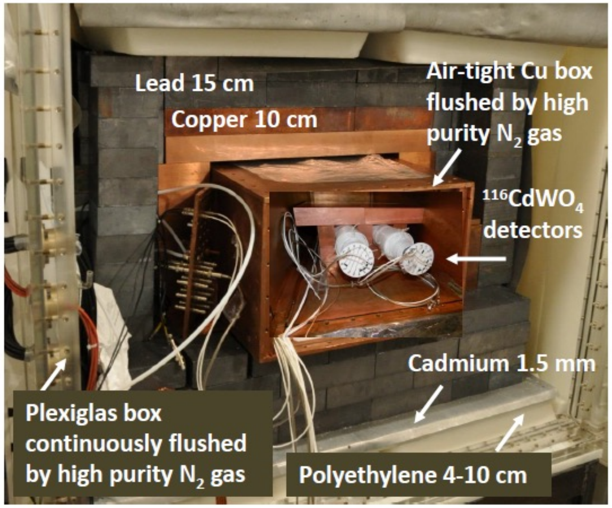
The most sensitive 0ν2β experiments (90% C.L.):

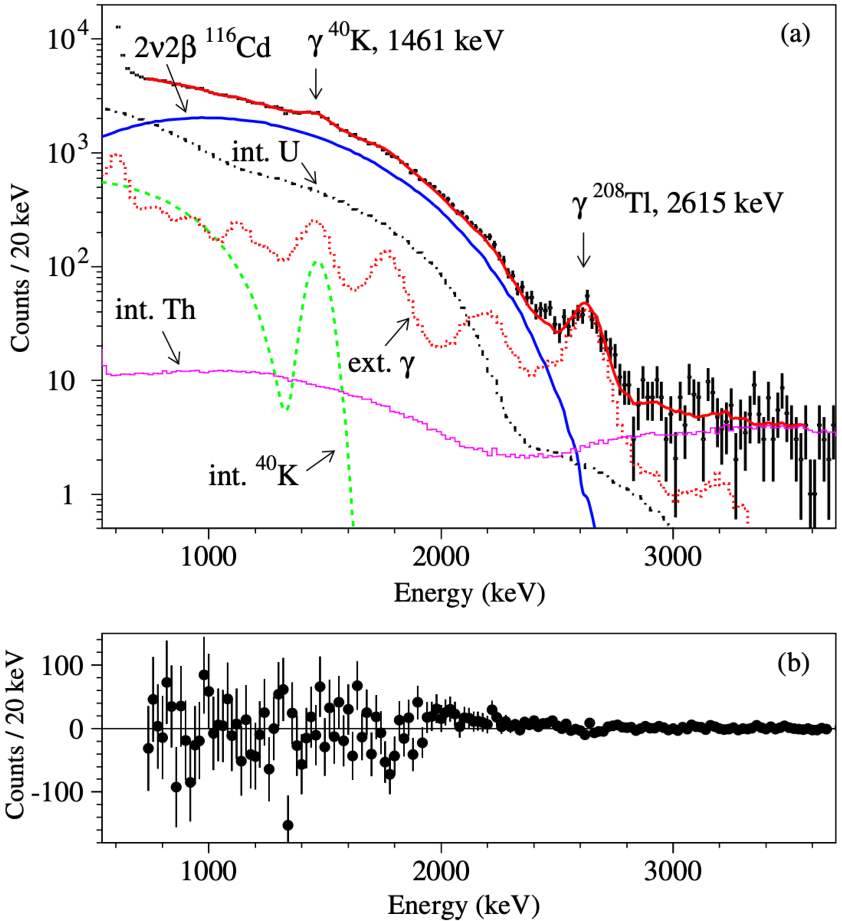
- Solotvina, F.A. Danevich et al., PRC 68 (2003) 035501 – $T_{1/2} > 1.7\ 10^{23}$ yr
- NEMO-3, R.B. Pahlka et al., Phys. Proc. 37 (2012) 1241 – $T_{1/2} > 1.3\ 10^{23}$ yr



Aurora experiment

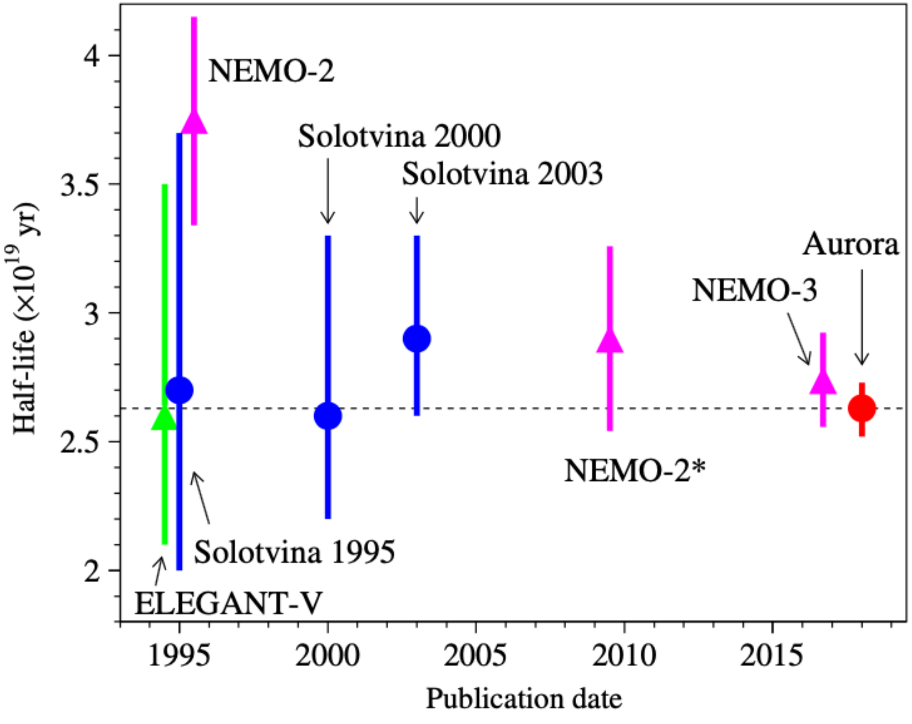
- to study 2β decay of ^{116}Cd with ^{116}CdWO$_4$ scintillators enriched at 82%
- at Gran Sasso in DAMA/R&D
- two cadmium tungstate crystals (580 g and 582 g)





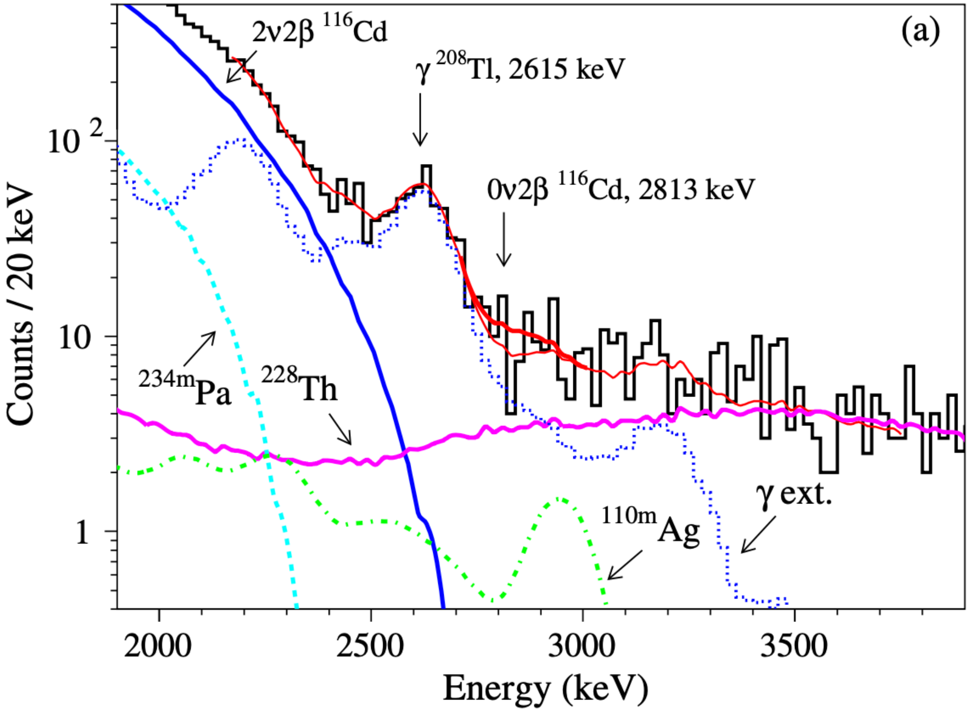
PRD98(2018)092007

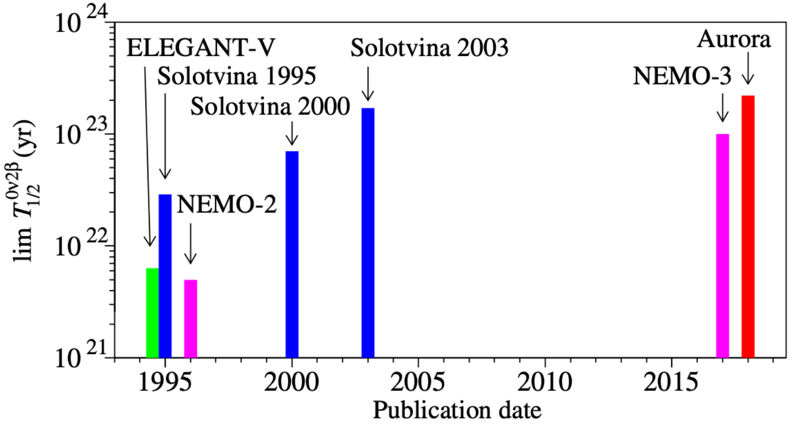
$$T_{1/2} = [2.630 \pm 0.011(\mathrm{stat})^{+0.113}_{-0.123}(\mathrm{sys})] \times 10^{19}\ \mathrm{yr.}$$

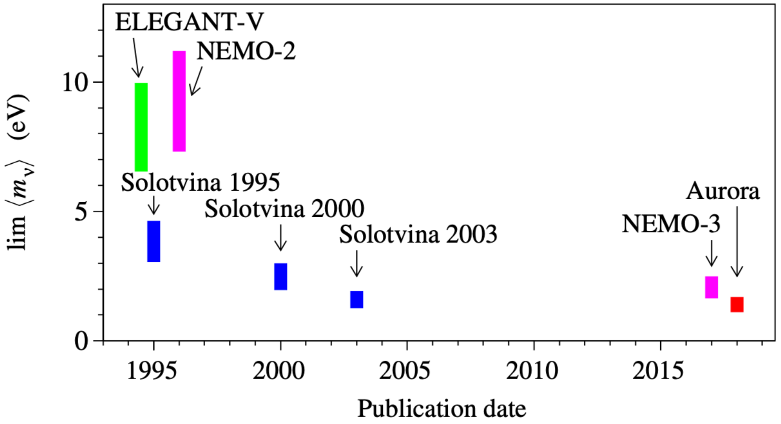


Aurora experiment ($0\nu2\beta$)

PRD98(2018)092007







$$T_{1/2} \geq 2.2 \times 10^{23} \text{ yr} \quad \text{at 90\% C.L.}$$

$$\langle m_\nu \rangle \leq (1.0 - 1.7) \text{ eV} \quad \text{at 90\% C.L.}$$

- ✓ **New** improved **limits** for 0ν2β decay of ^{116}Cd to excited levels of ^{116}Sn: lim $T_{1/2} \sim 10^{20}$–10^{22} yr and decays with majoron(s) emission: lim $T_{1/2} \sim 10^{21}$–10^{22} yr
- ✓ Main background, internal ^{228}Th, can be reduced 35 times by re-crystallization and sensitivity $T_{1/2}=5 \times 10^{23}$ yr can be reached in 5 yr

The best 2ε, $\varepsilon\beta^+$, $2\beta^+$ experiments

Nuclide	Channel	Experimental limits $T_{1/2}$ (yr)	Experimental method
^{40}Ca	2ε	$> (3\text{-}6) \times 10^{21}$	CaF_2(Eu) scintillators
^{54}Fe	2ε	$> (4\text{-}5) \times 10^{20}$	HPGe γ spectrometry
^{58}Ni	2ε, $\varepsilon\beta^+$	$> (0.2\text{-}7) \times 10^{20}$	HPGe γ spectrometry
^{64}Zn	2ε, $\varepsilon\beta^+$	$> 10^{18}\text{-}10^{21}$	$ZnWO_4$ scintillators
^{78}Kr	**2ε, $\varepsilon\beta^+$, $2\beta^+$**	**$> (1\text{-}5) \times 10^{21}$**	Gaseous detector
^{92}Mo	2ε, $\varepsilon\beta^+$	$> (0.06\text{-}9) \times 10^{20}$	HPGe γ spectrometry
^{96}Ru	**2ε, $\varepsilon\beta^+$, $2\beta^+$**	**$> (0.2\text{-}1.3) \times 10^{19}$**	HPGe γ spectrometry
^{106}Cd	**2ε, $\varepsilon\beta^+$, $2\beta^+$**	**$> (0.01\text{-}4) \times 10^{20}$**	HPGe γ spectrometry, NaI(Tl) γ spectrometry $CdWO_4$ scintillators CdZnTe semiconductor
^{130}Ba	**2ε, $\varepsilon\beta^+$, $2\beta^+$**	**$> 4 \times 10^{21}$** $= (2.2 \pm 0.5) \times 10^{21}$?	Geochemical
^{132}Ba	2ε	$> 2.2 \times 10^{21}$	Geochemical
^{120}Te	**2ε, $\varepsilon\beta^+$**	**$> (0.09\text{-}1.9) \times 10^{21}$**	TeO_2 cryo-bolometer

Motivation to study 2ε, εβ⁺, 2β⁺

$$(T_{1/2}^{0\nu})^{-1} = C_{mn}^{0\nu}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C_{m\lambda}^{0\nu}\langle\lambda\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right) + C_{m\eta}^{0\nu}\langle\eta\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right) + C_{\lambda\lambda}^{0\nu}\langle\lambda\rangle^2 + C_{\eta\eta}^{0\nu}\langle\eta\rangle^2 + C_{\lambda\eta}^{0\nu}\langle\lambda\rangle\langle\eta\rangle$$

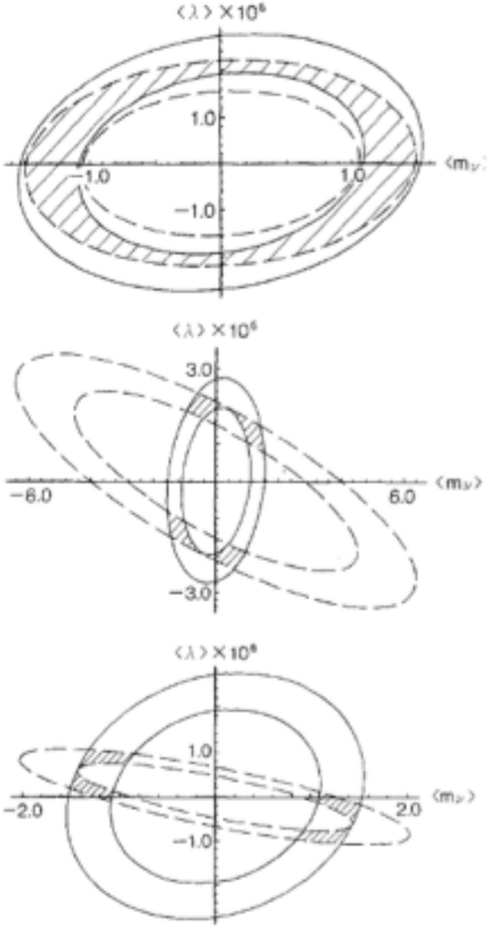
- **Right-handed weak current contribution**

Half-lives for 0νεβ⁺ decay depend strongly on whether the decay is dominated by the mass mechanism or right-handed weak current [1]

- **Possibility of resonant 0ν double electron capture**

- **The best experiments give only limits even for the two neutrino mode:**

$$T_{1/2} > 10^{18} - 10^{21}\ \text{yr}$$



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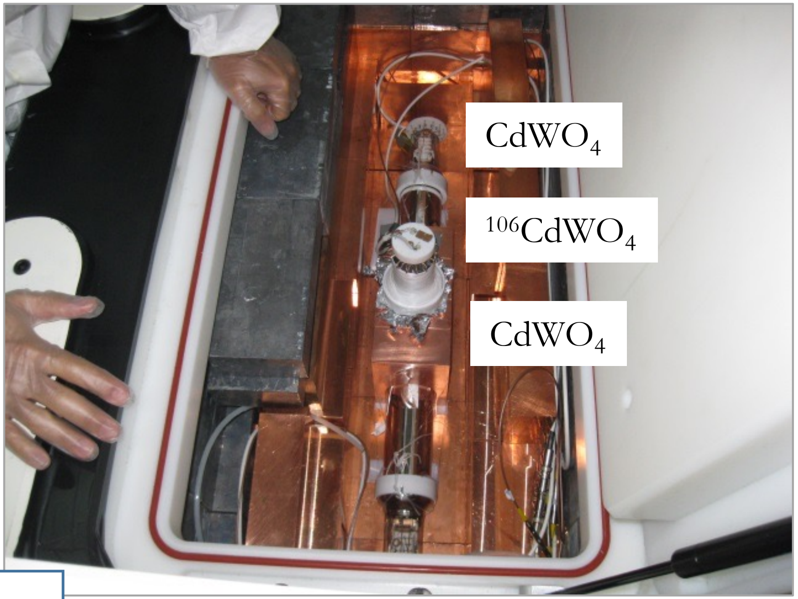
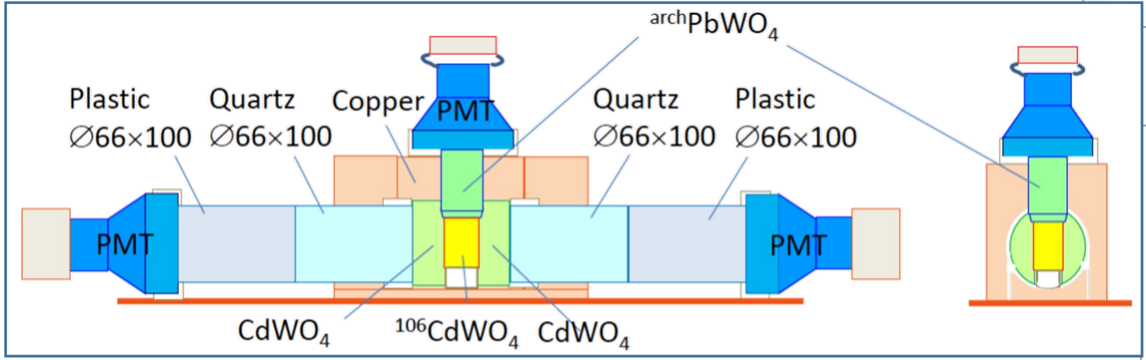
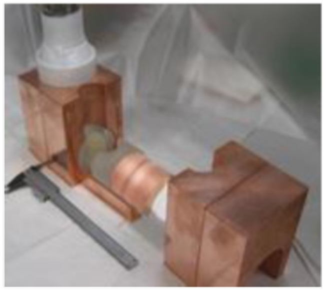
[1] M. Hirsch et al., Z. Phys. A 347 (1994) 151

^{106}Cd in DAMA/CRYS

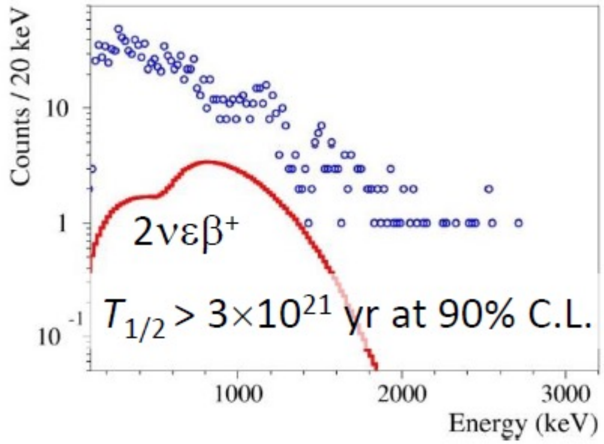
Experiment to search for 2β decay of ^{106}Cd with a $^{106}CdWO_4$ crystal scintillator (enriched in ^{106}Cd to 66%) in coincidence with two large $CdWO_4$ detectors in closed geometry is **in data taking.** After **14064 h**, the sensitivity to **$2\nu\varepsilon\beta^+$** is on the level of **$T_{1/2} > 3 \times 10^{21}$ yr** (theoretical predictions: $10^{20} - 10^{22}$ yr)



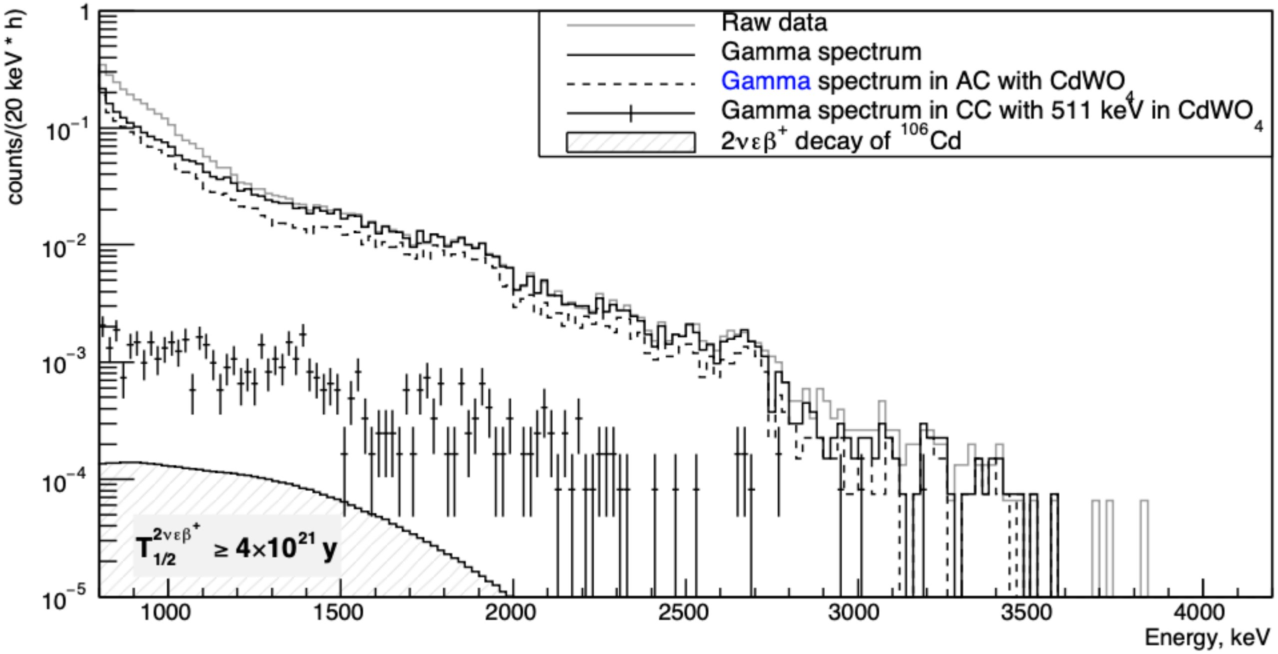




Energy spectrum over 11 910 h in CC with 511 keV in at least one of the $CdWO_4$



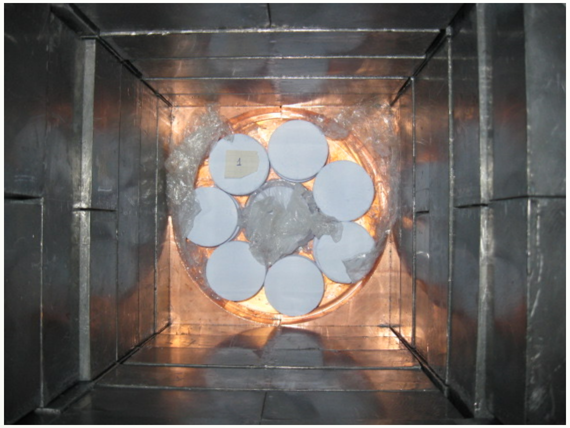
^{106}Cd in DAMA/CRYS (latest results)



Other double beta decay searches

- Search for 2β decays of ^{96}Ru and ^{104}Ru by ultra-low background HP Ge γ spectrometry **EPJA42(2009)171** **PRC87(2013) 034607**
- Investigation of rare nuclear decays with BaF_2 crystal scintillator contaminated by radium **EPJ A 50 (2014) 134**

  Analysis of Bi-Po events (half-life of ^{212}Po; search for 2β decay of ^{212}Pb); search for β and 2β decay of ^{222}Rn; search for 2β decay of ^{226}Ra



- Search for 2βdecay of ^{136}Ce and ^{138}Ce **NPA930(2014)195**

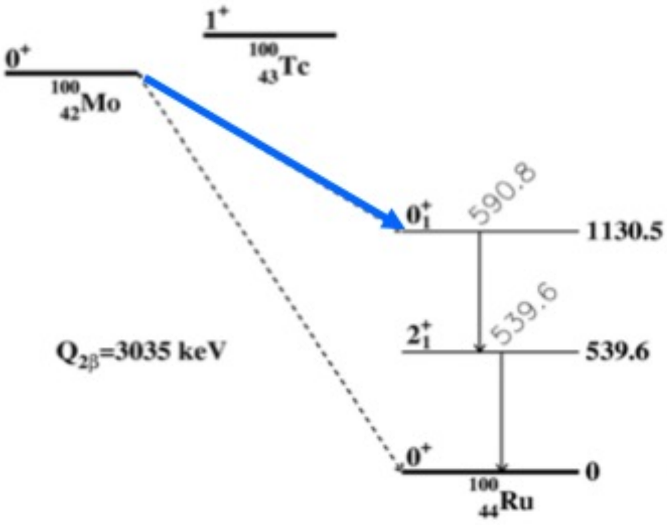
  Deeply purified CeO_2 sample (732 g) in HPGe (STELLA facility), T=1900 h
- A new kind of scintillator detector: $SrI_2(Eu)$ crystal scintillator. R&D in progress **NIMA670(2012) 10**
- Purification of Ce, Nd and Gd for low bckg experiments

  Liquid-liquid extraction technique to purify CeO_3, Nd_2O_3 and Gd_2O_3 from U/Th
- Study of 2β decay of ^{150}Nd to the excited states of ^{150}Sm

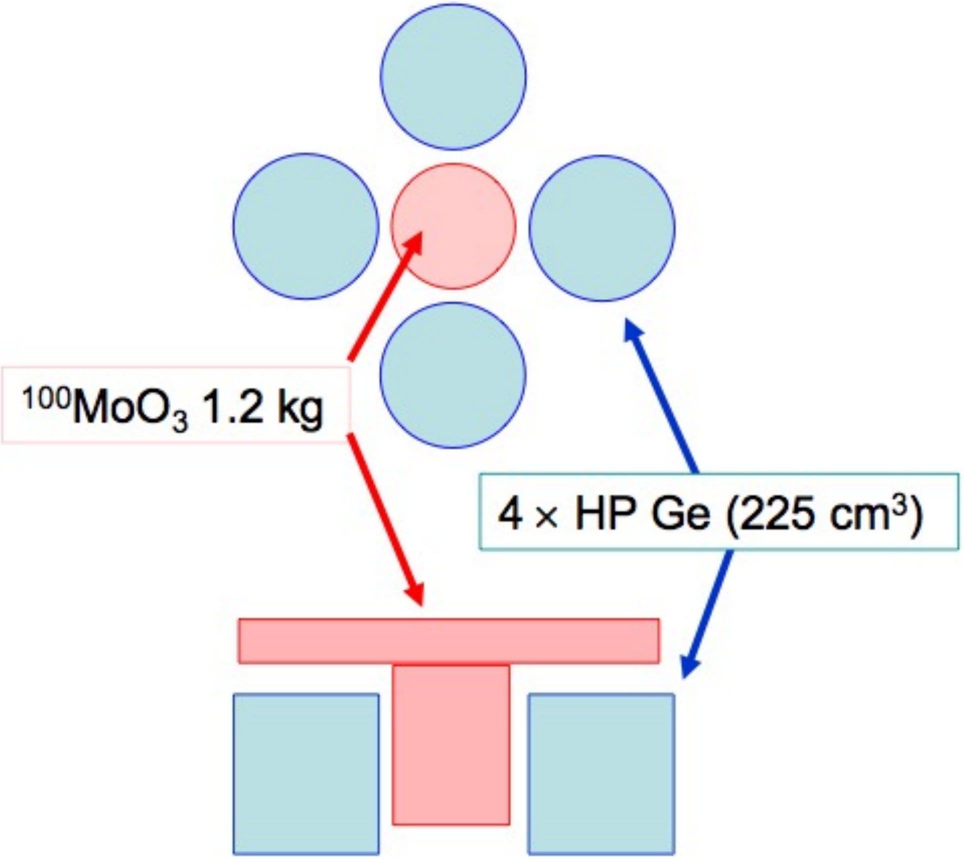
  A deeply purified Nd_2O_3 source (2.381 kg) was installed in GeMulti (4 HPGe ~220 cm^3 each) on 10 Feb 2015. $T_{1/2}(2\nu2\beta) = [4.7^{+4.1}_{-1.9}(\text{stat}) \pm 0.5(\text{syst})]\times10^{19}$yr

- First search for rare decays of Osmium by low background HPGe detector **EPJ A 49(2013)24**
- $ZnWO_4$ crystal scintillators (low bckg and large volume): double beta decay modes in Zn and W isotopes **PLB658(2008)193, NPA826(2009)256, NIMA626-627(2011)31, JPG: NPP 38(2011)115107**
- Search for long-lived superheavy eka-tungsten with radiopure $ZnWO_4$ crystal scintillator **Phys. Sc. 90 (2015) 085301**

ARMONIA: 2ν2β decay of ^{100}Mo to the 0_1^+ level of ^{100}Ru



1.2 kg of ^{100}MoO$_3$ 99.5%
HP Ge (225 cm^3 × 4) at LNGS



^{100}MoO$_3$ 1.2 kg

4 × HP Ge (225 cm^3)

^{100}MoO$_3$ (mBq/kg)	
^{40}K	36
^{226}Ra	2
^{228}Th	1

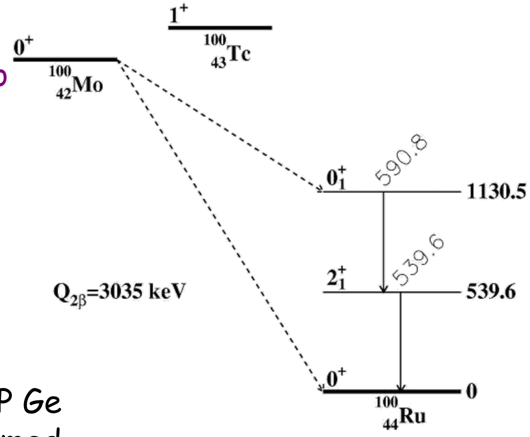
purification of enriched ^{100}Mo was carried out twice

Armonia

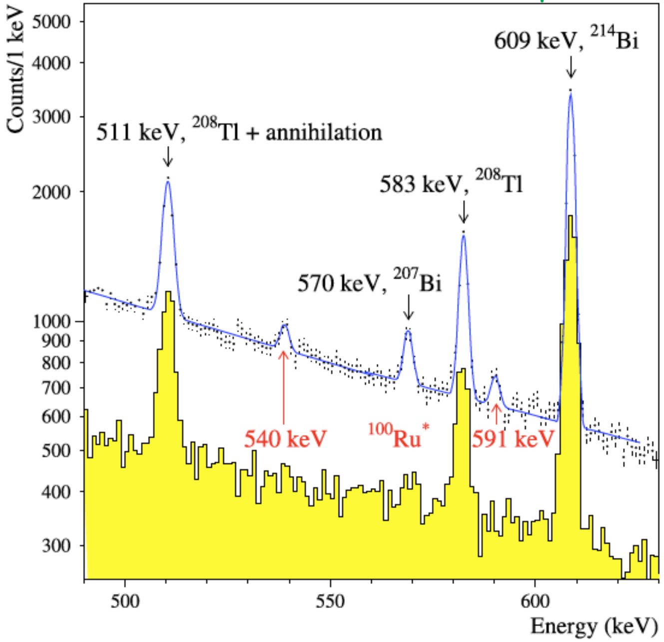
(meAsuReMent of twO-NeutrIno $\beta\beta$ decAy of ^{100}Mo to the first excited 0^+_1 level of ^{100}Ru)

NPA 846 (2010) 143

- $^{100}MoO_3$ sample (mass of 1199 g, enriched in ^{100}Mo at 99.5%) installed in the 4π low-background HP Ge detectors facility (4 HP Ge - about 225 cm^3 each - mounted in one cryostat) located in the underground Ge facility of the National Laboratory of Gran Sasso

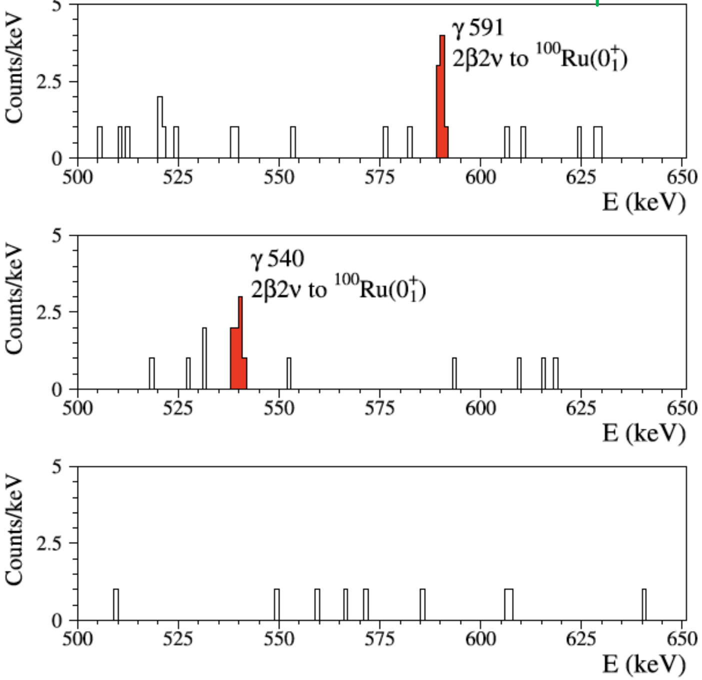


1-dim sum spectrum



- Aim: to measure the 2β2ν decay of ^{100}Mo to the the first excited 0^+_1 level of ^{100}Ru at E=1130.5 keV
- To point out the evidence of the decay searched for, an analysis considering the coincidence spectrum between any two HP Ge detectors in the set-up have been performed.

coincidence spectra



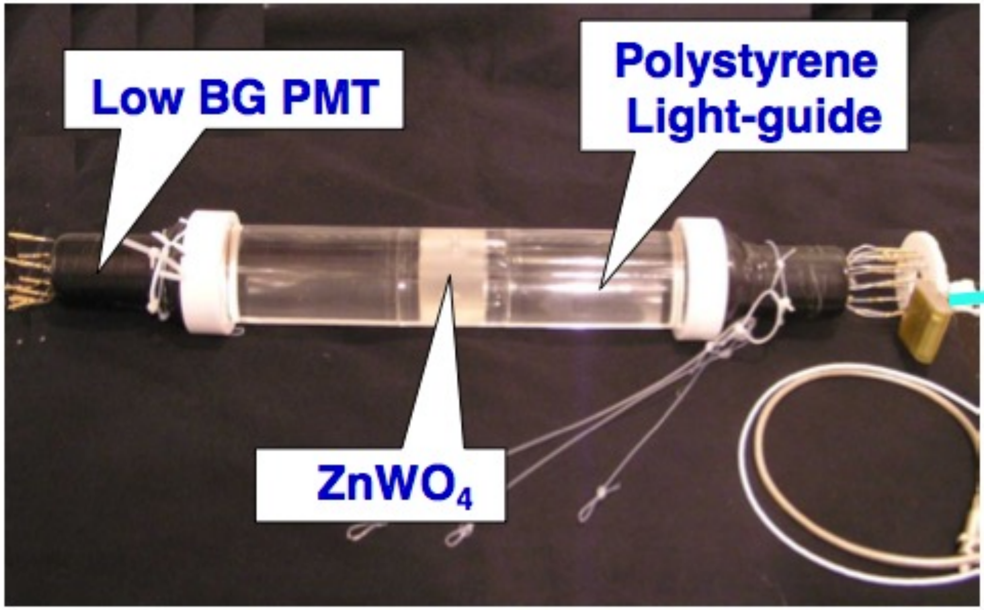
- 18120 h of measurements, 8 events are present in the coincidence spectrum, the measured half life is:

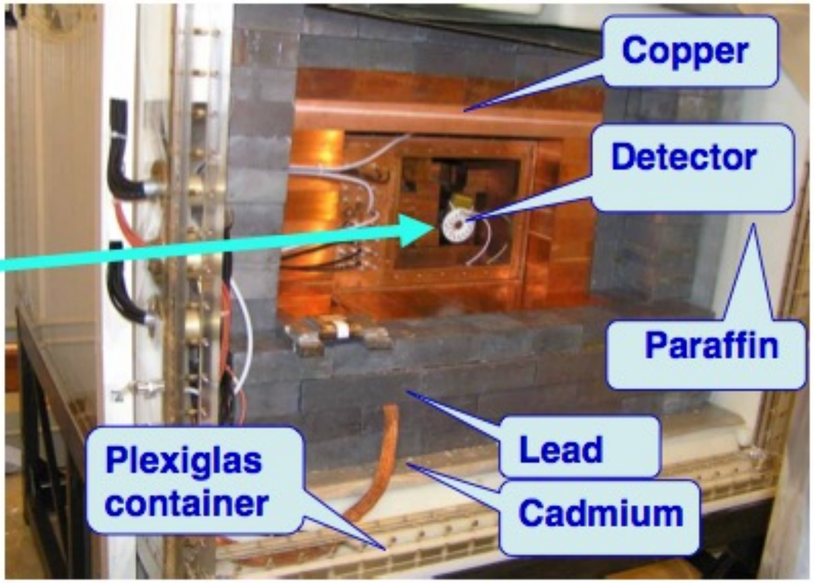
$$T_{1/2} = 6.9^{+1.0}_{-0.8}(stat.) \pm 0.7(syst.) \times 10^{20}\, yr$$

for ^{100}Mo →^{100}Ru* 2β2ν decay, in agreement with previous results, while the old limit $T_{1/2}$ >1.2 x 10^{21} yr is not confirmed.

2β decay of ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W with $ZnWO_4$ scintillators

DAMA R&D, Gran Sasso





Total exposure 193.5 kg × days

P. Belli et al., PLB 658 (2008) 193
P. Belli et al., NPA 825 (2009) 256

DAMA/Ge and STELLA facility ongoing

GeMulti (4 HPGe ~220 cm^3 each)

Highly purified Nd_2O_3 (2.38 kg) in measurement (so far **16375 h**) to investigate the 2β decay of ^{150}Nd to the first 0^+ 740.5 keV excited level of ^{150}Sm:

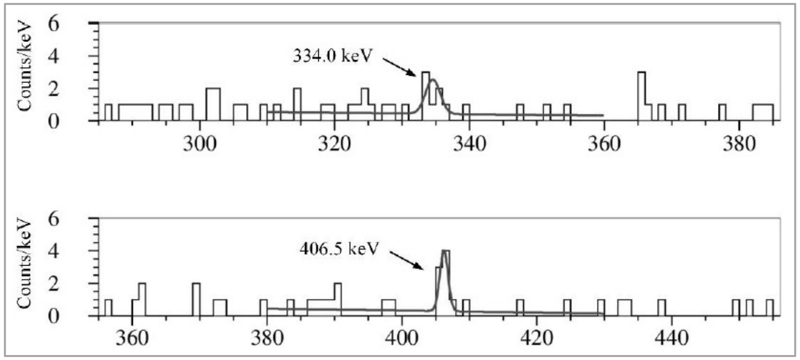
⇒ γ with energies **334.0 keV** and **406.5 keV** in coincidences in two HPGe **observed**;

⇒ $T_{1/2}=[4.8^{+4.1}_{-1.9}(stat) \pm 0.5\ (syst.)] \times 10^{19}$ yr

The experiment **will run at least one more year**.

Preliminary results published.

PRELIMINARY



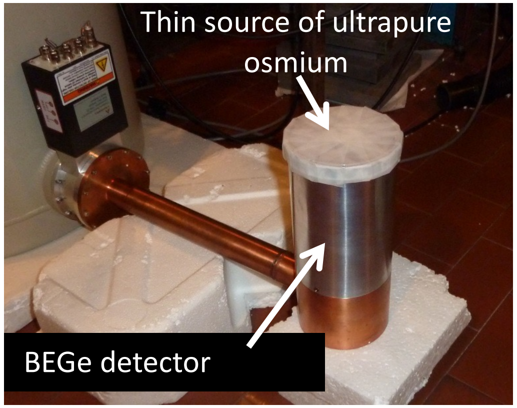
BEGe

118 g of ultra-pure Os in measurement to study rare α and ββ decays of Os isotopes.

⇒New limits on α decay of ^{184}Os and ^{186}Osm to the excited levels of ^{180,182}W:

$T_{1/2}$~theoretical expect.)

⇒Further plans: installation of the Os sample inside BEGe cryostat, to improve the detection efficiency



GeCris

326 g of deeply purified Er_2O_3, measured over 1934 h to search for the first time for 2ε and $\varepsilon\beta^+$ of ^{162}Er to the ground state and to several excited levels of ^{162}Dy:

⇒ No effect was observed: **$T_{1/2}$ limits on the level of ~ 10^{17} yr at 90% C.L.**

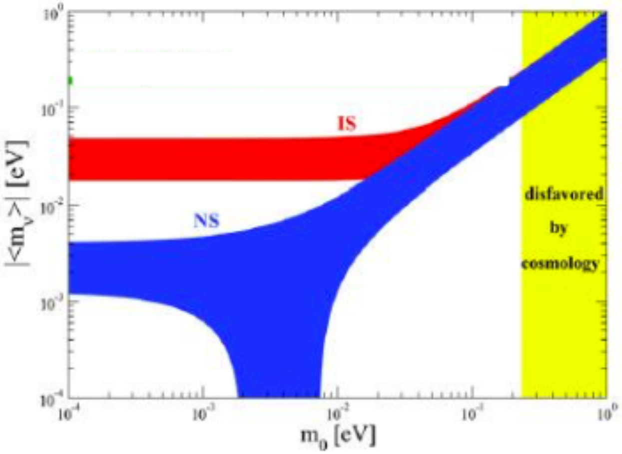
⇒ Improved limit on ββ decay of ^{170}Er to 83.4 keV excited level of ^{170}Yb: **$T_{1/2} > 4.1 \times 10^{17}$ yr.** Paper published.

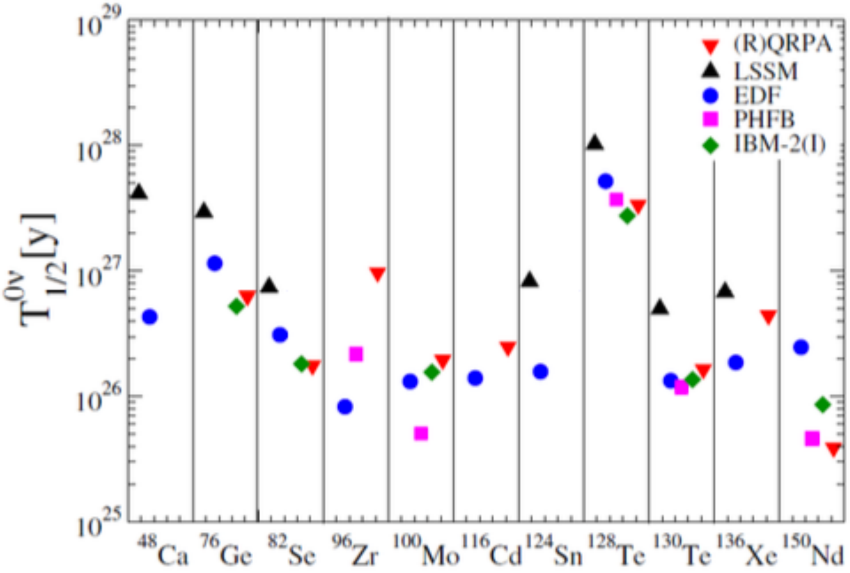
Future plans: First Experiments to **search for ββ decays of ^{144}Sm, ^{168}Yb, ^{154}Sm and ^{176}Yb** to the excited levels of daughter nuclei are **in progress** with highly purified samples installed on HPGe detectors of the STELLA facility, and more

The next generation experiments

should test the inverted hierarchy of the neutrino mass: $\langle m_\nu \rangle \sim 0.05$ eV

Theoretical calculations $T_{1/2}$ for $\langle m_\nu \rangle \sim 0.05$ eV [1]





Different nuclear models give rather different predictions

- **To test the inverted scheme of the neutrino mass we need sensitivity on the level of:**
  $\langle m_\nu \rangle \sim 0.05$ eB → $T_{1/2} \sim 10^{26} - 10^{27}$ yr
- **The possible quenching of the axial vector coupling constant (g_A) could amount to a multiplication of the half-lives by an order of magnitude [2] → $T_{1/2} \sim 10^{27} - 10^{28}$ yr**

[1] J.D.Vergados, H.Ejiri, F.Simkovic, Theory of neutrinoless double-beta decay ,Rep. Prog. Phys. 75 (2012) 106301
[2] J. Barea, J. Kotila, F. Iachello, Limits on Neutrino Masses from Neutrinoless Double-β Decay, Phys. Rev. Lett. 109 (2012) 042501

- *Goals and prospects*

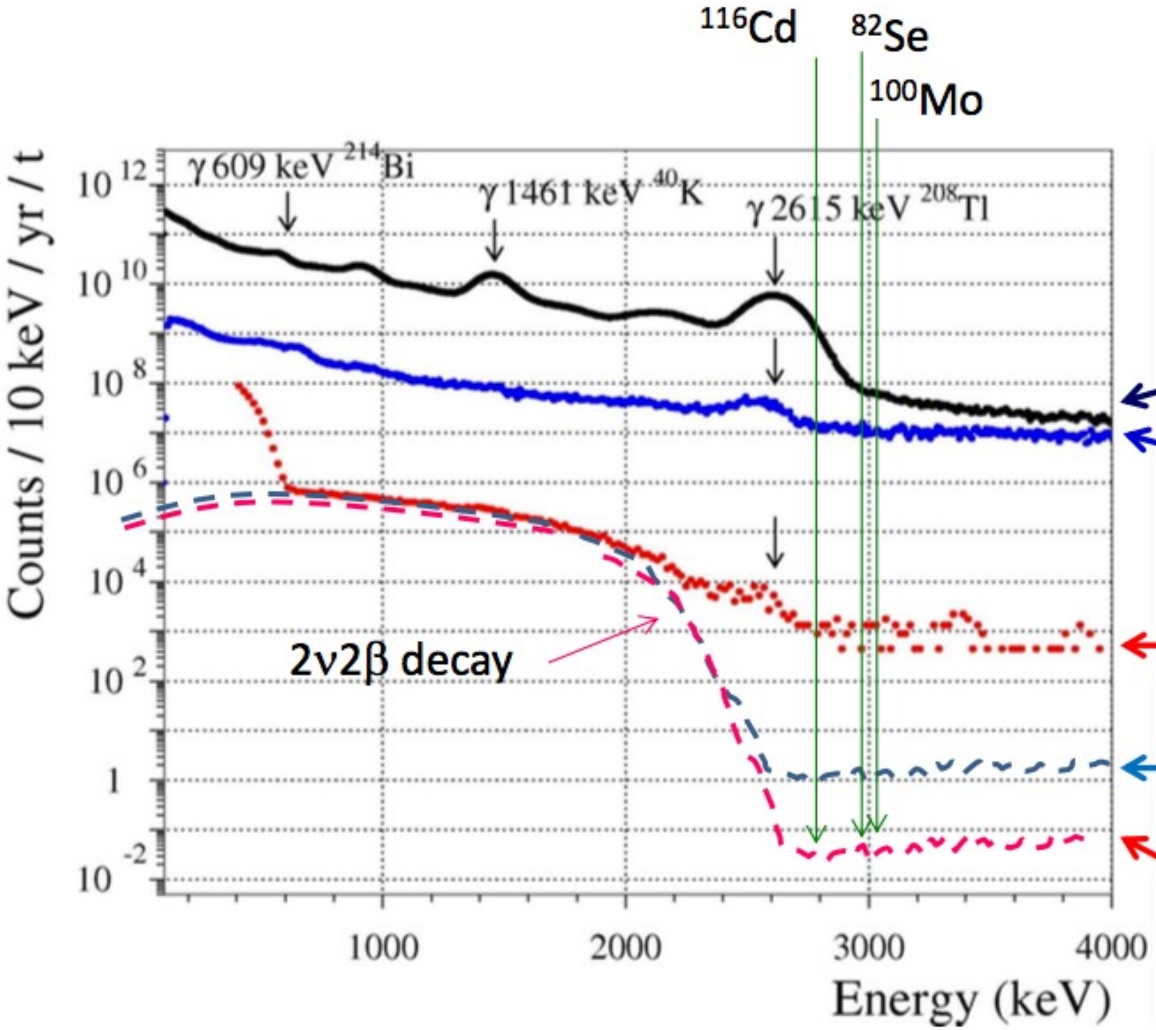
What does it mean $T_{1/2} \sim 10^{27} – 10^{28}$ yr ?

Nucleus	**$T_{1/2}$ to reach $\langle m_\nu \rangle = 0.02$ eV [1]**	**Detector**	**Number of 2β nuclei in 1 ton detector**	**Number of decays over 5 years**
^{48}Ca	**(3 – 28) ×10^{27} yr**	**^{48}CaF$_2$ (20%)**	**1.4×10^{27}**	**0.2 – 1.9**
^{76}Ge	**(3 – 17) ×10^{27} yr**	**HP ^{76}Ge**	**7.9×10^{27}**	**1.6 – 9**
^{82}Se	**(1 – 4) ×10^{27} yr**	**Zn^{82}Se**	**4.1×10^{27}**	**3 – 13**
^{100}Mo	**(0.3 – 1.5) ×10^{27} yr**	**Zn^{100}MoO$_4$**	**2.6×10^{27}**	**6 – 30**
		^{40}Ca^{100}MoO$_4$	**3.0×10^{27}**	**4 – 34**
		Li$_2$^{100}MoO$_4$	**3.4×10^{27}**	**8 – 39**
^{116}Cd	**(0.8 – 1.3) ×10^{27} yr**	**^{116}CdWO$_4$**	**1.7×10^{27}**	**4 – 7**
^{130}Te	**(0.7 – 3) ×10^{27} yr**	**^{130}TeO$_2$**	**3.8×10^{27}**	**4 – 18**
^{136}Xe	**(1 – 4) ×10^{27} yr**	**^{136}Xe**	**4.4×10^{27}**	**4 – 14**

[Nessun titolo]

[1] Table 3 in J.D.Vergados, H.Ejiri, F.Simkovic, Rep. Prog. Phys. 75 (2012) 106301

Significant background reduction is requested



CdWO$_4$ 2.2 kg no shield

CdWO$_4$ 2.2 kg
10 cv Cu, 5 cm Pb

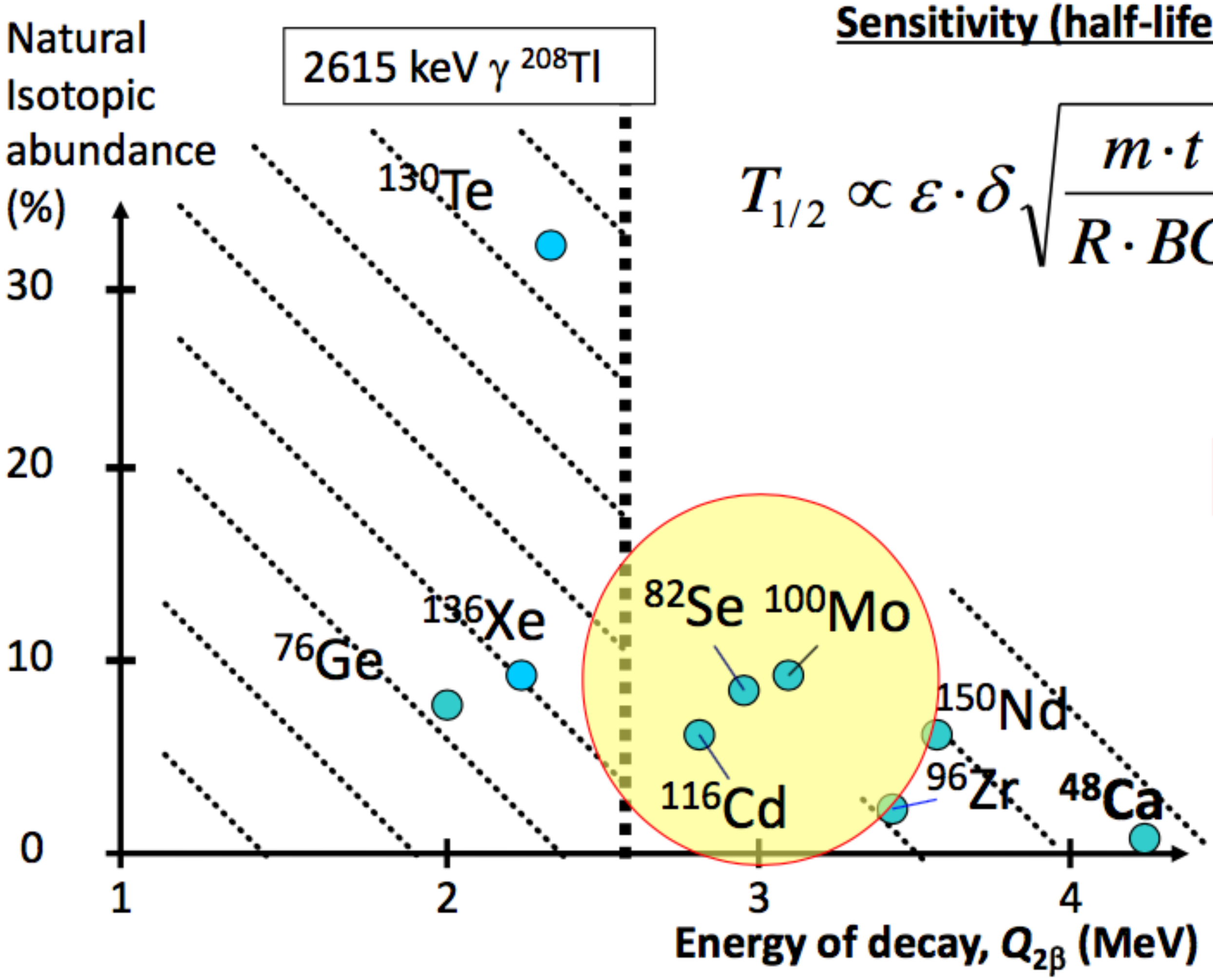
^{116}CdWO$_4$ 1.2 kg
DAMA R&D at LNGS

Next generation experiments

CUPID

- *Goals and prospects*

The most “promising” 2β nuclei



Sensitivity (half-life $T_{1/2}$) of 2β experiments:

$$T_{1/2} \propto \varepsilon \cdot \delta \sqrt{\frac{m \cdot t}{R \cdot BG}}$$

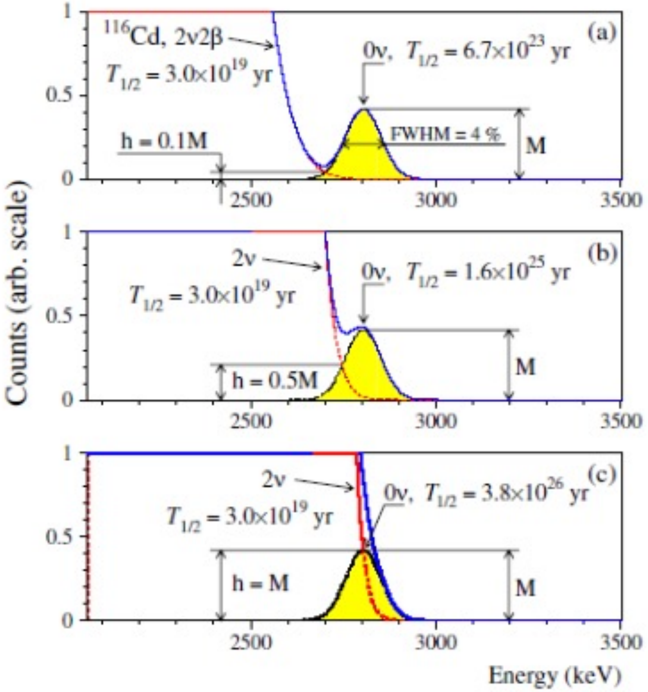
ε – detection efficiency
δ – concentration of 2β isotope
m **– mass of detector**
t **– time of measurements**
R **– energy resolution**
BG **– background**

- **Large $Q_{2\beta}$ > 2615 keV**

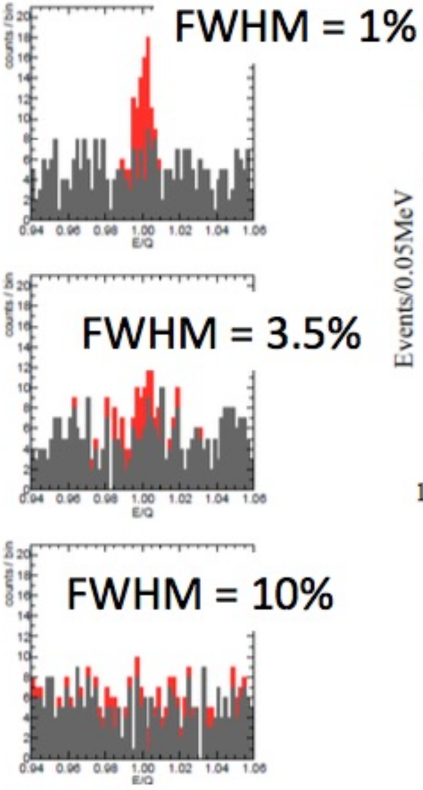
- **Enrichment ~ 10^2 - 10^3 kg**

- **High detection efficiency**
- **Low background**
- **High energy resolution**

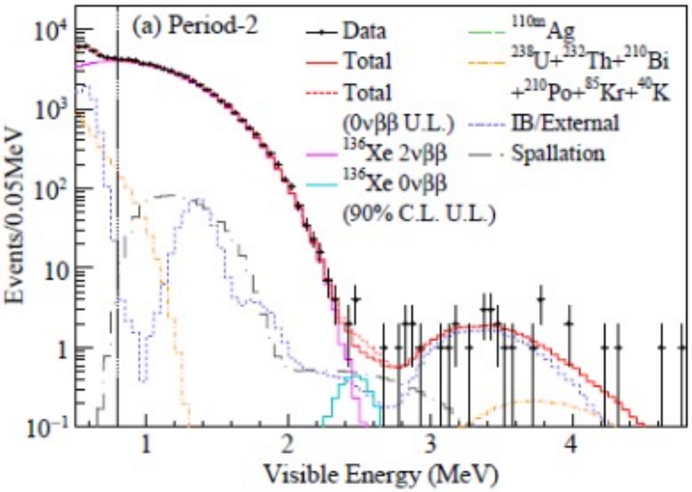
Energy resolution in 0ν2β experiments



Background in the ROI due to 2ν2β decay [1]



Visibility of 2ν2β peak [2]



KamLAND-Zen 2016

$$\text{FWHM} \approx 17\% / \sqrt{E(\text{MeV})}$$

A poor energy resolution is acceptable if one give a *limit* on 0ν2β decay, while it is not a case if one claim *detection* of the process

[1] Yu.G. Zdesenko, F.A. Danevich, V.I. Tretyak, Sensitivity and discovery potential of the future 2*β* decay experiments, J. Phys. G: Nucl. Part. Phys. 30 (2004) 971

[2] J.J. Gómez-Cadenas and J. Martín-Albo, Phenomenology of Neutrinoless Double Beta Decay, PoS (GSSI14) 004

Conclusions

Exciting times for neutrino masses:

- degeneracy will be deeply probed
- discovery potential in case of inverted hierarchy